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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

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SECTION 7
VOLUME III
EMP ENGINEERING HANDBOOK
FOR GROUND BASED FACILITIES

JULY 1983

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7.0 HARDNESS MAINTENANCE AND SURVEILLANCE TEST AND SUPPORT EQUIPMENT

The proper performance of EMP hardness maintenance and surveillance tests requires the use of a wide variety of test and support equipment. This section discusses the characteristics, operation, and limitations of various types of test and support equipment required to perform the tests and inspections.

The primary frequency range of interest for maintenance and surveillance tests and inspections is 10 kHz to 100 MHz. However, some organizations perform tests outside this frequency range, and, in some cases, specific tests are performed outside this frequency range. Other typical frequency ranges are 100 Hz to 100 MHz, 10 kHz to 400 MHz, and 100 kHz to 1 GHz. Where possible or appropriate, the characteristics of test equipment over the 100 Hz to 1 GHz frequency range are discussed in an attempt to accommodate as many applications as possible.

7.1 ENERGY SOURCES AND SIMULATORS

A large variety of energy sources is used in EMP hardness testing. The types of sources vary from large multi-megavolt simulators capable of generating threat level radiated environments to low power CW signal generators. The type of energy source used for a particular test depends on a number of factors including the objective of the test, the level of the test point in the EMP hardness hierarchy, and whether the response being evaluated is linear or nonlinear. If the objective is to evaluate the total system response to an EMP environment with a single test, then it will be necessary to illuminate the complete facility with a large radiating simulator capable of generating a threat level environment. For direct injection testing, it is only necessary to simulate signals that are representative of the energy that would be coupled to the component or port under test; and hence, medium power sources are usually adequate. For tests to evaluate linear characteristics such as shielding effectiveness, transfer functions, and broadband impedance characteristics where no arcing or breakdown are involved, low power CW sources are usually adequate.

7.1.1 CW Sources

Many of the hardness maintenance and surveillance tests involve the excitation of the system with a CW signal. Continuous wave testing is particularly beneficial for maintenance and surveillance testing since single frequency comparisons can be made quickly and relatively inexpensively (as compared to the cost of equipment required for pulse testing). Thus, some aspects of hardening degradation due to system modifications and aging can be efficiently determined with CW testing.

The generation of CW signals can be accomplished with a multitude of commercially available signal generators or frequency synthesizers. Signal generators generally consist of an oscillator utilizing a resonant cavity or circuit with mechanical tuning that provides fundamental frequencies over a relatively narrow range, typically an octave or less. Figure 7.1-1 is a block diagram of the basic elements of a signal generator. In order to achieve a broader frequency range, the oscillator's fundamental output frequency is multiplied or divided. Proper filtering then suppresses the spurious outputs caused by the division or multiplication process. The generator then amplifies and levels these filtered outputs to insure a controllable, accurate output over a broad frequency range. To improve stability many signal generators incorporate a frequency-lock feature which monitors the output frequency and provides corrective signals to the resonant device.

Frequency synthesizers derive all their output frequencies from a fixed reference frequency and therefore have frequency characteristics which are extremely accurate and stable. A synthesizer's output is digitally programmable in small frequency increments, rather than continuously as with signal generators. Generally, synthesizers fall into two basic types, direct and indirect. Nearly all commercially available synthesizers utilize indirect synthesis; however, they may also contain a lower frequency direct synthesizer that provides the required frequency resolution.

Direct synthesis is accomplished by first generating a number of secondary reference frequencies in increments equal to the smallest ouput step size. This is done through a series of programmable frequency multiplications and divisions of the reference. Next, the appropriate secondary references are added or subtracted by mixer frequency conversions to generate the final output frequency. An example of a direct synthesizer is shown in

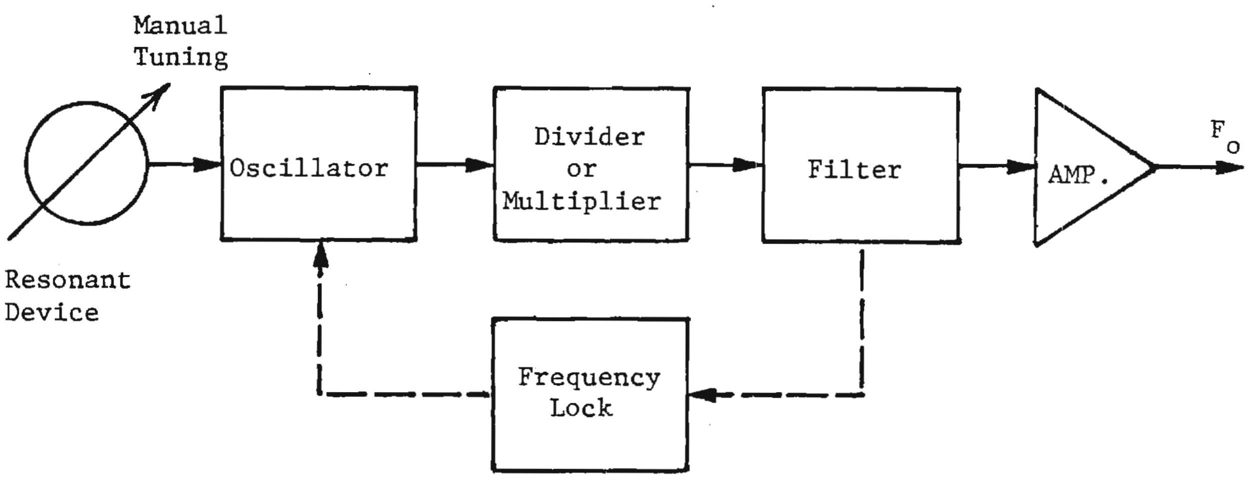


Figure 7.1-1. Basic Elements of a Signal Generator.

Figure 7.1-2. This example shows how a 10-MHz reference oscillator is used to generate a 51.1 MHz output signal. Direct synthesis has the advantage of fast frequency switching and simple digital control. However, the direct technique requires a large number of complex filters to remove spurious and undesired sidebands that result from the mixing processes, and the circuitry tends to be quite complex if a wide programming range is desired along with small frequency steps.

Indirect synthesis represents a more cost-effective approach for applications that involve a wide range of output frequencies and can tolerate slower switching times. Figure 7.1-3 shows the basic harmonic multiplication approach to indirect synthesis. A voltage contolled oscillator, phase-locked to a harmonic of the reference oscillator, generates the output frequency locally. Small frequency steps are obtained by dividing the reference frequency down to the minimum frequency step size and using a combination of phase-locked loops to derive the final output frequency. Due to the response time of the phase-locked loop, the switching time of indirect synthesizers is much slower than direct synthesizers (tens of milli-seconds versus tens of micro-seconds).

Table 7.1-1 lists typical performance specifications for commercially available signal generators and frequency synthesizers applicable to maintenance and surveillance testing. Signal generators offer the signal integrity and spectral purity inherent in cavity tuning. Frequency synthesizers are characterized by precise frequency accuracy and stability. The power output of both types of CW sources is somewhat limited for hardness testing; however, when they are used in conjunction with commonly available broadband RF amplifiers these limitations are easily overcome. External modulation input ports are available on both signal generators and frequency synthesizers. This feature is often needed in order to produce the various waveforms required in the hardness testing. With the continuing emphasis on automation and programmable instruments, signal generators are emerging with microprocessor enhancements offering limited programming. Synthesizer technology was developed with the automation movement, and full programmability is the rule rather than the exception.

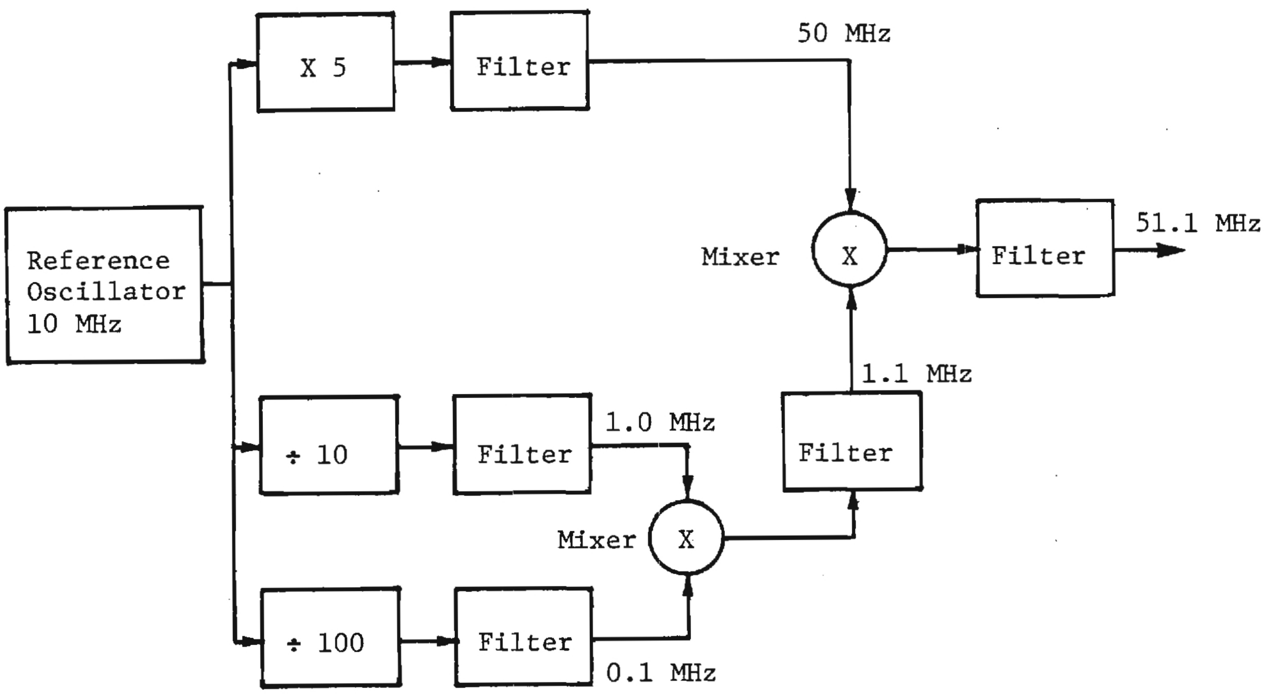


Figure 7.1-2. Example of a Direct Frequency Synthesizer, Illustrating How a 10 MHz Reference Oscillator Can Be Used to Generate a 51.1 MHz Signal.

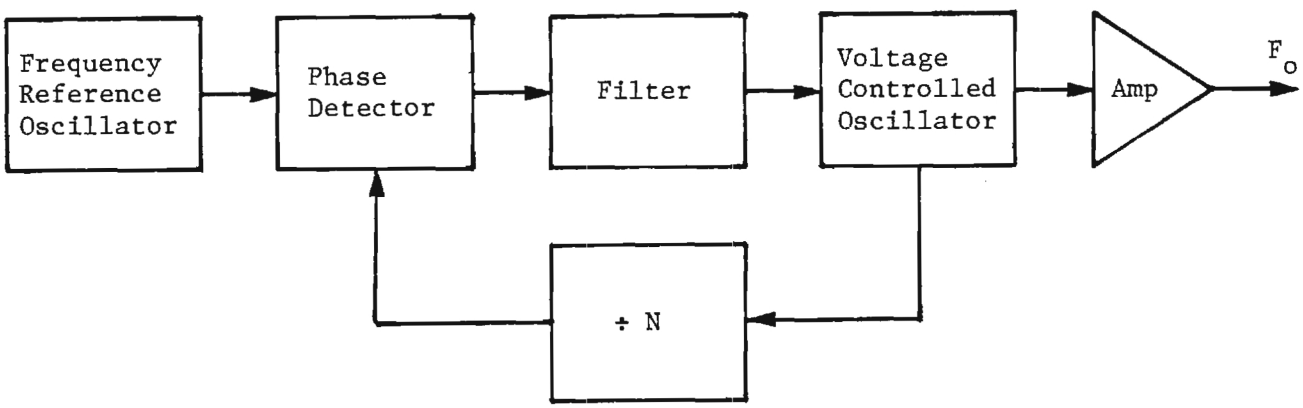


Figure 7.1-3. Basic Elements of an Indirect Frequency Synthesizer.

TABLE 7.1-1.

TYPICAL CHARACTERISTICS OF COMMERCIALLY AVAILABLE CW GENERATORS

TYPE	FREQUENCY RANGE	STABILITY	MAXIMUM OUTPUT LEVEL (into 50 Ω)	SPURIOUS CONTENT	MODULATION	OPERATION MODES
Signal Generators	LF Signal Generator: 1 Hz - 1 MHz RF Signal Generator: 0.5 MHz-1000 MHz	± .01% 10^{-5}/day	+20 dBm	Harmonic -20 to -30 dBc Spurious -100 dBc	AM FM External	Manual Limited Programming
Frequency Synthesizers	LF Frequency Synthesizer: 1 MHz - 20 MHz RF Frequency Synthesizer: 20 kHz-1200 MHz	10^{-8}/day 10^{-10}/day	+13 dBm	Harmonic -20 to -30 dBc Spurious -50to-80dBc	AM FM External	Manual Fully Programmable

Typical CW Source Generator Suppliers

John Fluke Mfg. Co.	Everett, WA
Hewlett-Packard Co.	Palo Alto, CA
Marconi Electronics, Inc.	Northvale, NJ
Watkins-Johnson Co.	Palo Alto, CA
Wavetek	San Diego, CA

7.1.2 Swept CW Sources

Swept-frequency CW measurements not only save considerable time but provide substantially more information than discrete CW testing. Swept-frequency techniques are used in hardness maintenance testing to determine the shielding effectiveness of cables, enclosures, and conduits as a function of frequency. Other applications for sweep generators include measuring transfer characteristics, impedance, VSWR (voltage standing wave ratio), and reflection coefficients.

Commercially available sweep generators utilize frequency determining resonant devices and are configured similar to signal generators. Figure 7.1-4 shows the block diagram of a typical sweep generator. The automatic tuner sweeps the output frequency by tuning the resonant cavity/circuit through a given frequency range, at a controllable precise rate. In order to maintain a constant output level, a sweep generator generally has an automatic level control (ALC) incorporated in its amplification stage. A sample of the output is fed back to this feedback system and is used to provide a highly accurate and constant output level. This feedback signal is either provided by an internal or an external detector. An accurate method for determining frequency is generally provided through calibrated frequency markers. These markers are generated with a crystal-controlled comb generator for precise frequency stability.

Many modern sweep generators also incorporate microprocessors in their design providing automated measurement capabilities. Other features which are built into these programmable sweep generators include the following: increased accuracy and resolution of both output frequency and output power; flexible frequency marker capabilities for each selection and determination of frequency parameters; programmable sweep ranges and speeds; swept power output capabilities; and self-check or diagnostic capabilities.

Frequency synthesizers can also be used to perform swept-frequency measurements approaching a continuous sweep by stepping the output frequency in fine increments. Through digital control, the output frequency can be swept through its entire range or through specified bands. Frequency synthesizers used as sweepers must be able to switch between frequencies both phase-continuously and transient free. Frequency resolution and switching speed are important parameters for synthesizers used as sweepers, since they

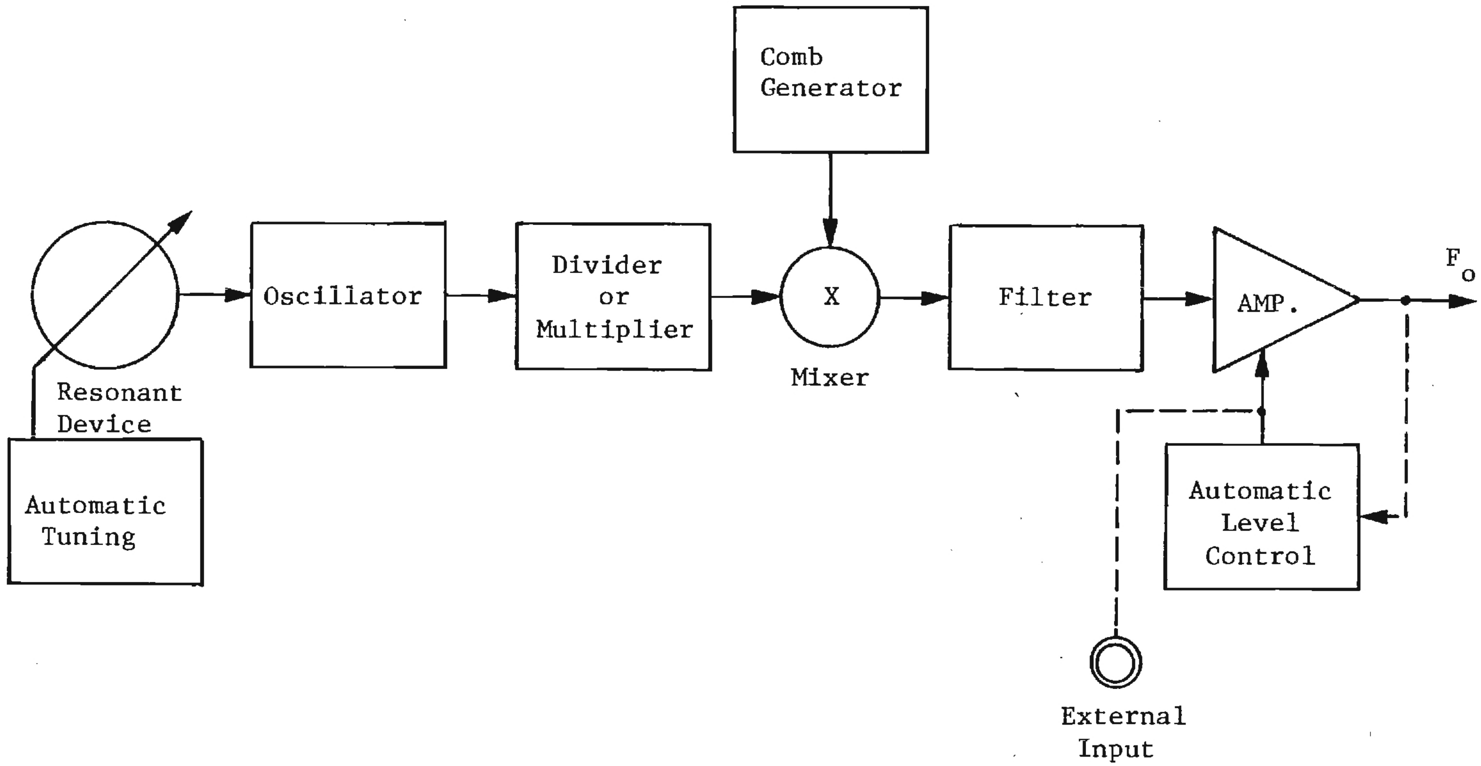


Figure 7.1-4. Basic Elements of a Sweep Generator.

determine the smallest step size achievable and the fastest sweep rate achievable. Many synthesizers offer logarithmic frequency sweeps as well as linear frequency sweeps. The inherent digital nature of frequency synthesizers make them fully programmable, offering such features as preset sweep start/stop frequencies, center frequencies, bandwidths, sweep speeds, etc.

Typical performance characteristics of commercially available swept CW sources are given in Table 7.1-2. Sweep generators offer continuous frequency sweeps while synthesized sweepers switch frequencies in increments which are sufficiently small, for most applications, to be truly representative of a continuous sweep. Output flatness of swept sources varies considerably from manufacturer to manufacturer and from instrument to instrument for a single manufacturer. Some offer flatness as low as $\pm$ 0.2 dB with ALC utilizing external detectors; however, this limit does not include detector variations. Sweep time is a parameter which also varies considerably from instrument to instrument. Sweep generators typically have sweep times which are continuously variable between a minimum and maximum speed, while synthesized sweepers have discretely selectable sweep times.

7.1.3 Transient Voltage/Current Generators

A wide variety of transient energy sources (pulsers) are used in EMP hardness testing. These pulsers vary in complexity from small laboratory pulse generators used for component testing to large sophisticated multi-megavolt systems used in large-scale, radiating EMP simulators. The large multi-megavolt pulse sources are normally custom designed for the radiating simulator requirements. A wide variety of pulse sources are commercially available with voltage ranges from a few volts to a few hundred volts and current ranges from milliamps to several amps. When used in conjunction with wide-band power amplifiers and impedance-matching units, peak output voltages up to 30 KV and peak output currents up to 750 amps can be obtained.

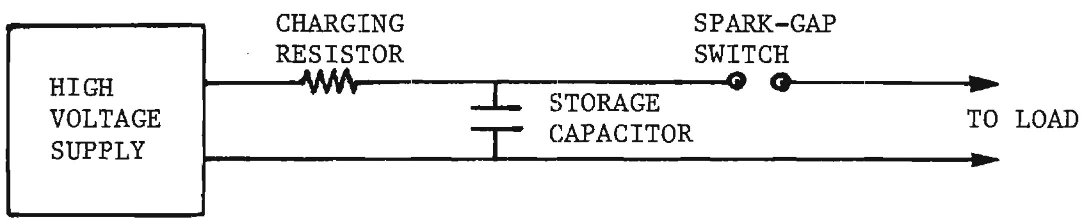
The basic configuration of commercially available pulse sources is normally one of the two configurations shown in Figure 7.1-5. The basic capacitor discharge circuit, illustrated by the block diagram in Figure 7.1-5(a), consists of a high voltage power supply, a storage capacitor, a current limiting charging resistor, and a switch for connecting the storage capacitor to the load. The storage capacitor is charged by the high voltage

TABLE 7.1-2.

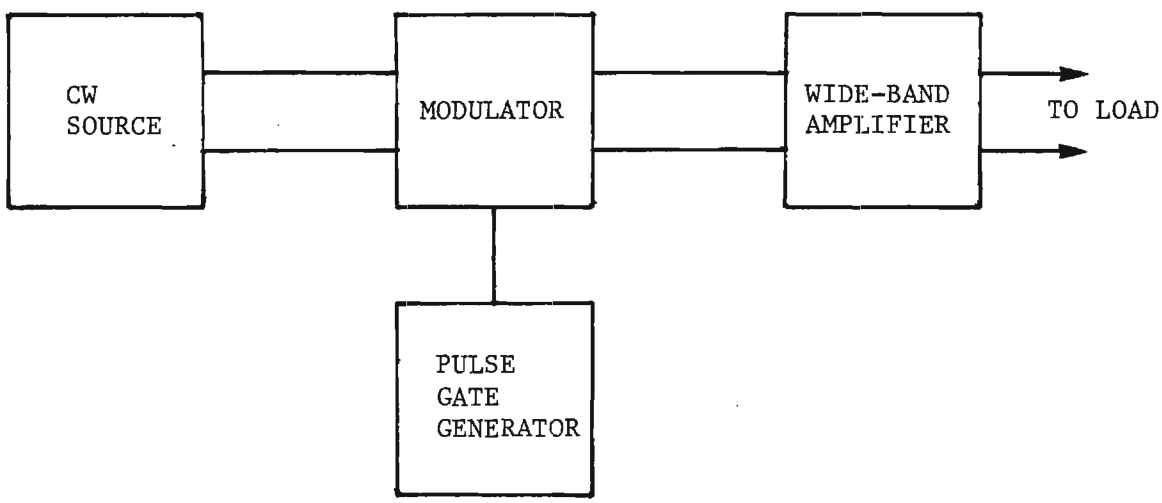
TYPICAL CHARACTERISTICS OF COMMERCIALLY AVAILABLE SWEPT CW SOURCES

TYPE	FREQUENCY RANGE	FREQUENCY RESOLUTION	MAXIMUM OUTPUT LEVEL (into 50 Ω)	OUTPUT FLATNESS	SWEEP TIME (Full Band)	OPERATION MODES
Sweep Generators	LF Sweep Generators: 100 kHz-100 MHz RF Sweep Generators: 10 MHz-1 GHz	Continuous	+13 dBm	± 1.0 dB	Variable 20 mS to 100 S	Manual Limited to Fully Programmable
Frequency Synthesizers	LF Synthesized Sweeper: 1 Hz-20 MHz RF Synthesized Sweeper: 100 kHz-1 GHz	.001 Hz to 1 Hz	+13 dBm	± 1.0 dB	log, linear Variable 10 mS to 100 S	Manual Fully Programmable

Typical Sweep Generator Suppliers	
Eaton Corp.	Los Angeles, CA
John Fluke Mfg. Co.	Everett, WA
Hewlett-Packard Co.	Palo Alto, CA
Watkins-Johnson Co.	Palo Alto, CA
Wavetech	San Diego, CA



(a) Capacitor Discharge Configuration



(b) Modulated CW Configuration

Figure 7.1-5. Basic Configurations for Pulse Sources.

supply through the charging resistor. When the voltage on the capacitor reaches the breakdown potential of the spark-gap switch, the switch closes and discharges the capacitor into the load. The output waveform is a pulse with a very short rise time and a longer decay time. The rise time of the output pulse is determined by the inductance of the capacitor and its connecting wiring. The decay time is determined by the value of the storage capacitor and the load impedance. The basic capacitor-discharge circuit may be modified, as illustrated in the top four circuits of Table 7.1-3, to produce a double exponential, rectangular, or damped sinusoidal output waveform.

The basic modulated CW pulser circuit, illustrated by the block diagram in Figure 7.1-5(b), consists of a CW source, a modulator, a gate generator, and an amplifier. The CW signal from the CW source is passed through the modulator to the amplifer during the pulse gate period. This circuit can produce a damped sinusoidal or an RF burst output waveform as illustrated in the bottom two circuits in Table 7.1-3. Several key parameters which should be considered when selecting a particular type pulser are listed in Table 7.1-3.

Typical characteristics of commercially available pulse sources and several pulse source suppliers are listed in Table 7.1-4.

7.1.4 Transportable EMP Simulator

Transportable EMP simulators are sometimes used to perform facility hardness maintenance or surveillance tests. The simulators are transportable in that they can be moved to a test site, assembled, and operated. After the tests are completed, the simulators can be disassembled, relocated, and used again at another facility. The transportable simulators range from ones that must be transported by several tractor trailers to ones that can be transported in a station wagon. The simulators may be capable of generating threat-level environments, or they may only be capable of generating subthreat levels.

TABLE 7.1-3.

SUMMARY OF PULSE SOURCE
TYPES AND WAVEFORMS

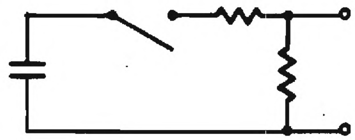
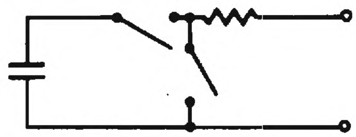
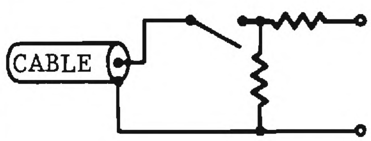
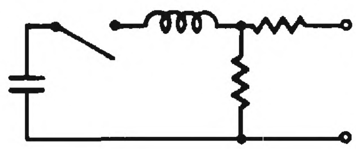
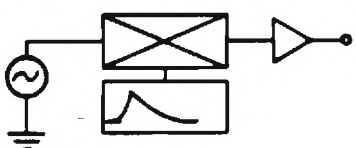
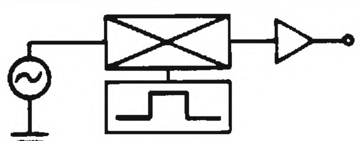
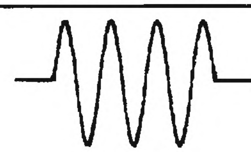
TYPE	CIRCUIT	WAVEFORM	PARAMETERS
CAPACITOR DISCHARGE		 DOUBLE EXPONENTIAL	VOLTAGE SOURCE IMPEDANCE RISETIME FALL TIME
CROWBAR		 RECTANGULAR PULSE	VOLTAGE SOURCE IMPEDANCE RISETIME PULSE WIDTH
CABLE DISCHARGE		 RECTANGULAR PULSE	VOLTAGE SOURCE IMPEDANCE RISETIME PULSE WIDTH
RESONANT		 DAMPED SINUSOID	VOLTAGE SOURCE IMPEDANCE FREQUENCY DAMPING (Q)
MODULATED CW		 DAMPED SINUSOID	VOLTAGE SOURCE IMPEDANCE FREQUENCY DAMPING (Q)
MODULATED CW		 RF BURST	VOLTAGE SOURCE IMPEDANCE FREQUENCY PULSE WIDTH

TABLE 7.1-4.

TYPICAL CHARACTERISTICS OF COMMERCIALLY AVAILABLE PULSE SOURCES

TYPE	WAVEFORMS	PEAK VOLTAGE (Volts)	PEAK CURRENT (Amps)	RISE TIME	FALLTIME	OPERATION MODES
LOW POWER	DOUBLE EXPONENTIAL RECTANGULAR PULSE DAMPED SINUSOID RF BURSTS	10-100	2	7-35 ns 7-35 ns	7ns-50ms 7-50ns	MANUAL PROGRAMMABLE
MEDIUM POWER	DOUBLE EXPONENTIAL RECTANGULAR PULSE DAMPED SINUSOID RF BURSTS	100-1,000	5	7-35 ns 7-35 ns	7ns-50ms 7-50ns	MANUAL PROGRAMMABLE
HIGH POWER	DOUBLE EXPONENTIAL RECTANGULAR PULSE DAMPED SINUSOID RF BURSTS	1,000-20,000	10-15	7-35 ns 7-35 ns	7ns-50ms 7-50ns	MANUAL PROGRAMMABLE

TYPICAL PULSE SOURCE SUPPLIERS	
EG&G	Albuquerque, NM
Maxwell Labs, Inc.	San Diego, CA
Physics International, Inc.	San Leandro, CA
Tobe Deutchmann Labs.	Canton, MA
Velonix	Santa Clara, CA

7.1.4.1 Types of Transportable Simulators. Two types of transportable simulators are used to simulate EMP environments. One type is a wave simulator which generates an electromagnetic wave to illuminate the entire facility or system-under-test. The other type is an injection simulator that simulates the EMP environment indirectly by injecting currents and voltages on conductors external to the facility or system-under-test. The wave simulator may be either a radiating or bounded wave (transmission line) class, and the injection simulator may be either a current or voltage class. The wave simulator can also be classed as hybrid. The hybrid class of simulators are constructed by combining features of a radiating and static (low-frequency) simulator. On a hybrid simulator, the high-frequency portion of the waveform is radiated from a relatively small part of the overall simulator, while the low-frequency portions of the waveform are associated with the currents and charges distributed over the entire structure.

The bounded wave simulator excites and guides an electromagnetic wave in a transmission line. The system or facility being tested is located within the transmission line and is exposed to the excited electromagnetic wave. The essential elements of this simulator include an energy source, transition sections, a test volume, and a termination. An electromagnetic wave is excited by a pulser or CW generator connected at one end of the transmission line, and the wave propagates to the termination end. The pulser or generator is connected to the transmission line using transition sections having constant impedance. At the termination end, a resistive load absorbs the electromagnetic wave to prevent reflections on the line. To obtain field uniformity in the bounded wave simulator, the system or facility under test must be small in relation to the size of the test volume. The bounded wave simulator is capable of generating high-level fields since the available energy is contained in or bound to the space within the transmission line. In general, the bounded wave simulator produces only a single polarization (normally vertical) and a single angle of arrival. For smaller systems, different polarizations and angles of arrival can be achieved by rotating the system within the test volume.

The radiating wave simulator may be either a dipole or long-wire antenna. These simulators have an energy source, a biconical matching section located at the antenna center, and a wire structure that forms the antenna arms. The wire structure may be resistively loaded or have distributed impedance loading along the arm length. An important advantage of the radiating simulator is that the test region is not limited by the structure's dimensions. The disadvantage of such a simulator is that only a fraction of the available energy is directed to the system-under-test, due to the relatively nondirectional radiation of the dipole antenna. Futhermore, there is a geometrical 1/R attenuation of the radiated wave amplitude with distance. This attenuation causes a difficult tradeoff between field level and field planarity. For the dipole radiating wave simulator, the polarization and angle of arrival can be changed by positioning the dipole. For the long-wire antenna, the available polarization is predominately horizontal on the line normal to the dipole axis and through the feed point of the bicone. Angle of arrival from the long-wire is changed by changing the position of the system-under-test.

An injection simulator consists of a pulser or CW generator that is fed to an external conductor. The output of the pulser or generator may be coupled indirectly by a cable driver or directly by hard wiring the simulator output into a cable or transmission line. The injection simulation can generate the equivalence of high-level EMP environments at far less power and cost compared to the wave simulator. Furthermore, the conductor or cable under test can be isolated and studied singularly. The main disadvantage associated with direct injection testing is that the actual free field coupling to the total system cannot be simulated. Correctly phasing and shaping the pulses for a multiport injection system can be very difficult. Also, depending on the point of injection, any nonlinear effects may or may not be resolved.

Radiating or injection simulators may be capable of simulating either threat or sub-threat levels. A threat-level simulator can normally generate only one threat-level pulse every 6-10 minutes. These simulators tend to have a high failure rate. A sub-threat simulator can normally deliver several pulses per minute with a smaller failure rate. The time between pulses and the time between failures are significant factors for facility testing, since these times impact the time necessary for data collection. Many test technicians prefer to work with simulators having a fast repetition rate because it makes data collection easier. On the other hand, most analysts prefer single shot data because they are certain what the incident field was when the data was measured. In general, low-level, fast-repetition simulators are used mostly for diagnostic-type data collection where the quantity of data is important, and threat-level simulators are used for certification-type data collection where quality is more important.

7.1.4.2 Characteristics and Features of Transportable EMP Simulators.

EMP Wave Simulators*

Table 7.1-5 sumarizes the characteristics and features of several EMP wave simulators including the TEMPS, REPS, VEMPS, SUITCASE, RES-1, TEFS, and SEIGE 1. Each of these simulators is described briefly.

TEMPS

The Transportable EMP Simulator (TEMPS) was conceived and specified by HDL and sponsored by DNA. The simulator was designed and constructed by Physics International. The TEMPS is a threat-level, hybrid simulator which takes the form of a biconical wave launcher and a cylindrical wire-cage dipole. The wire cage can be varied in length in 100 meter increments to a maximum of 300 meters. The cage is 30 feet in diameter and is supported horizontally above ground on dielectric towers at elevations up to 20 meters as measured from the antenna centerline to ground. The cylindrical cage ends are returned to earth ground through the use of tapered conductor sections and each end of the antenna is resistively terminated.

The TEMPS pulser, located at the midpoint of the wire cage dipole, is a bilateral, gas-insulated pulse generator which drives the 120-ohm biconical wave launcher. In operation, two 35-stage Marx generator-peaking capacitor electrical circuits are dc charged (100 kv maximum) in about 40 seconds. The two pulsers are connected back-to-back and synchronously timed with a jitter of only a few nanoseconds. The generators charge their respective peaking capacitors in about 65 nanoseconds, at which time the preset output switch closes, discharging the pulser in series with the wire-cage dipole. The

*C. E. Baum, "EMP Simulators for Various Types of Nuclear EMP Environments: An Interim Categorization," IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-20, No. 1, February 1978, pp. 35-53.

TABLE 7.1-5

TRANSPORTABLE EMP WAVE SIMULATIONS

SIMULATOR	CONTACT	TYPE	BURST SIMULATED	SIZE (meters)	PULSER VOLTAGE	RISE TIME	PULSE CROSSOVER	PULSE REP RATE	MAXIMUM ELECTRIC FIELD	POLARIZATION
TEMPS	HDL	Pulse Radiating	Exoatmospheric Threat Level	300 L	7 MV	8 ns	800 ns	one pulse per 10 minutes	50 KV/m (50m)	Horizontal, on Centerline
REPS	HDL	Pulse Radiating	Exoatmospheric Sub-threat Level	300 L	1 MV	5 ns	800 ns	one pulse per 4-60 seconds	8 KV/m (50m)	Horizontal, on Centerline
RPC	HDL	Pulse Radiating	Exoatmospheric Sub-threat Level	50-300 L	250 KV	4 ns	200-800 ns	one pulse per second	1.8 KV/m (50m)	Horizontal, on Centerline
VEMPS	HDL	Pulse Radiating	Exoatmospheric Sub-threat Level	20 H	50 KV	10 ns	65 ns	one pulse per 2-10 seconds	0.4 KV/m (50m)	Vertical
SUITCASE PULSER	AFWL	Pulse Radiating	Exoatmospheric Sub-threat Level	70 L	125 KV	4 ns	400 ns	one pulse per second	0.8 KV/m (50m)	Horizontal, on Centerline
RES-1	AFWL	Pulse Radiating	Exoatmoshperic Sub-threat Level	60 L (Hor) 183 L (Vert)	1.6 MV	4-5 ns	70 ns	one pulse per second	3.75 KV/m (100m)	Horizontal, or Vertical
TEFS	NSWC (White Oak)	Bounded Wave	Exoatmospheric Sub-threat Level	12 L 6 W 6 H	--	40 ns	300 ns	--	5 KV/m	Horizontal or Vertical
SIEGE	AFWL SAMSO	Transmission Line	Surface	50 L 50 W 30 H	300 KV	10-20 ns	500 ns	--	80 KV/m	Vertical

pulser has an energy content of 6 kilojoules, an overall length of 31 feet, and weighs about 14,000 pounds.

The electromagnetic wave launched from the biconical wave launcher is horizontally polarized when located on a centerline perpendicular to the launcher. The polarization changes as a result of the interaction of the initial EM wave with the nearby earth medium, and the field distribution becomes essentially vertically polarized as the EM wave expands. Basically, each one-half of the dipole acts as a transmission line above a ground plane to yield the vertical polarization. Good wave planarity can be achieved within a test region that measures 50 X 50 meters and is centered on a line perpendicular to the pulser.

The TEMPS is a complete simulator system and includes an instrumentation van, a data recording system, a computer aided handling and analysis system, and support facilities.

REPS

The Repetitive Electromagnetic Pulse Simulator (REPS) was designed and built by Physics International under contract to HDL. The REPS is a transportable, sub-threat level simulator having a variable pulse repetition rate, with intervals being adjustable from 4 to 60 seconds. The simulator was specifically designed to perform field illumination tests on the power plants at SAFEGUARD MSR and PAR sites. The REPS is a horizontal dipole antenna and has a cylindrical wire cage that is nine feet in diameter, and the antenna is supported at a height of 50 feet by a transportable wooden structure. Each end of the wire cage is tapered and terminated in a resistive load.

The REPS pulser has an adjustable output from 750 kilovolts to 1.25 megavolts and produces an output pulse with a rise time of seven nanoseconds and a fall time of 800 nanoseconds. Within the pulser, a 16-stage, triggered Marx generator provides a total usable energy storage capability of 1.7 kilojoules. The unusually fast output rise time is obtained by using a very low inductance pulser output circuit consisting of a 200 pF self-healing gas peaking capacitor in conjunction with a self-breaking spark gap in an atmosphere of sulfur hexafloride. All command and control functions are linked between the pulser and a small trailer via pneumatic lines or fiber optics. Primary power is transmitted from the trailer to the pulser by a high pressure hydraulic line. A hydraulic motor in the pulser drives an alternator which provides all pulser electrical power. These techniques result in complete electrical isolation between the pulser and the ground except at the terminating ends.

The field generated by the REPS is horizontally polarized when observed on a centerline perpendicular to the pulser biconical section. The span of uniform coverage is 25 meters on each side of the centerline at 50 meters from the pulser. Over this test region the peak fields vary less than ten percent. The angle of incidence of the electric field at 50 meters from the pulser is 18 degrees when the pulser is at a maximum height of 15 meters.

RPG

The Repetitive Pulse Generator (RPG) was designed and fabricated in-house at HDL for testing various penetrations at SAFEGUARD RSL sites. The RPG was the first wave simulator specifically used to assess the attenuation of large structures. The simulator is designed to be very portable and adaptable to a wide variety of support structures. Its main function is to provide a high-repetition-rate EMP source for diagnostic and quick-look data. The RPG is a horizontal dipole antenna and has a cylindrical wire cage that is 40 inches in diameter. By adding sections, the length of the dipole can be adjusted between 50 to 300 meters. A pulser containing a Marx generator is used as the energy source and the pulser has a 250-kilovolt output. The pulser can produce one pulse every second. Polarization is horizontal when observed on a centerline perpendicular to the pulser. The span of uniform coverage is dependent upon the particular test setup, and the angle of incidence of the electric field is dependent upon the pulser height relative to the system-under-test.

VEMPS

The Vertical Electromagnetic Pulse Simulator (VEMPS) is a prototype high-frequency, fast rise-time vertical simulator, and was designed to support tests that require predominantly vertical fields on systems such as communication equipment with whip antennas. The VEMPS simulator is a vertical wire cage that is 20 meters high with a cone angle of 56 degrees at the lower apex and an angle of 14 degrees at the upper apex. At its maximum diameter, the wire cage is four meters. The shape of the antenna was designed to give a clear-time of approximately 10 nanoseconds. A 50-foot diameter, aluminum-screen ground plane is used with the antenna cage.

A specially constructed pulser is used to drive the VEMPS, and the pulser is located in a steel reinforced concrete tank under the ground plane. The pulser contains a spark-gap type switch in a sulfur hexaflouride pressurized plexiglass container. In this design, a capacitor bank of 1380 picofarads is charged to a point where the switch self-fires and the resultant voltage is discharged into the apex of the wire cage. The pulser is driven by 110 volts ac which is converted of 50 kilovolts dc. The output pulse is a double exponential with approximately 30 percent undershoot and with a first crossover at 65 nanoseconds. The free field generated by the VEMPS is uniform around the antenna at any given distance.

SUITCASE PULSER

The SUITCASE PULSER (SP) is a miniature, transportable, sub-threat simulator with a high pulse repetition rate. The simulator was designed to be completely self-contained, transportable in a station wagon, and to be set up in one hour for tests in remote areas. Its main function is to provide a reliable EMP source for diagnostic tests in areas without electric power or other utilities. A 125-kilovolt pulser is contained within the simulator, and the pulser drives a 30-meter horizontal dipole antenna with a 20-meter wire extending from each end to ground. The output pulse is a double exponential with less than 20-percent undershoot, and the first crossover occurs at 400 nanoseconds. The span of uniform coverage depends on the test setup, and the angle of incidence of the electric field depends on the height of the pulser and the location of the system-under-test.

RES-1

The Radiating EMP Simulator (RES) was built for the Air Force Weapons Laboratory. The simulator is a lightweight, sub-threat level, high-altitude simulator consisting of a pulse source and a dipole antenna that can be operated while suspended from a helicopter. When the dipole is carried horizontally, a length of 60 meters is used, and when carried vertically a 183-meter length may be used. Ground based versions of the RES also exist, but in this configuration, the ends of the antenna are resistively connected to earth ground. The antenna structure uses a distributed resistive coating to attenuate the antenna current to minimize reflections. A 150-ohm biconical wave launcher is used at the center of the diplole to guide the EM wave from the switch region to the nine-foot cylindrical dipole antenna.

The center of the antenna is fed by a pulser system which consists of a 1.6 Mv Marx generator, a water dielectric transfer capacitor, and an output switch. The Marx has 16 stages and is gas-insulated at a few psi in a five-foot diameter aluminum cylinder. The pulser weighs about 3,000 pounds. It charges the water capacitor in about one microsecond. In series with the capacitor is a 100 psi SF_6 switch that self-closes to discharge the system into the antenna. The output waveform is a double exponential pulse. The low frequency content is limited due to the short physical length of the antenna. A unique feature of the RES-1 is its ability to provide all angles of arrival since it is airborne.

TEFS

The Transportable Electromagnetic Field Simulator (TEFS) is a bounded-wave transmission line simulator with multiple feeds that is designed to propagate a transient in the vertical downward direction. Five hundred and seventy-six transition sections, each with a line impedance of 200 ohms are used. Four transitions are paralleled and driven from a 50-ohm cable.

The cables (144 total) are commonly driven from a single switch and capacitor bank. The 144 sections can be configured in a variety of ways to illuminate an area of 40 X 40 meters. A field of 50 kV/m is provided with a four nanosecond rise time and a decay time constant of 350 nanoseconds.

Versions of this simulator are available at the White Sands Missile Range, New Mexico, and the Naval Surface Weapons Center, White Oak Laboratory test facility at Patuxent Naval Air Station.

SIEGE

The Simulated EMP Ground Environment (SIEGE) simulator is a bounded-wave transmission-line type with multiple feeds or transition sections. This simulator is designed to test a buried facility or system. A buried transmission line is employed to propagate low frequencies down into the earth in the vicinity of a buried facility near the ground surface. Vertical rods are used to earth guide a lossy TEM wave propagating downward. At the bottom of the rods, the wave is reflected, but the severe attenuation avoids significant resonant effects. Low-frequency considerations require that the depth of the rods be larger than their spacing, and several times the depth of the facility-under-test. At the top of the transmission line, a current path is provided to connect the two rod arrays to a source. One version of this simulator is at the Air Force Weapons Laboratory.

Injection Simulators

Several different types of transportable injection simulators are available. The types include cable drivers, direct injection, current injection, and inductively coupled. Brief descriptions of selected injection simulators are presented below.

1020 Cable Driver

Cable driver techniques consist of injecting a transient current of known waveform onto the external electrical shield of a multistrand cable and then measuring the currents induced into the internal conductors. The 1020 cable driver facility was developed by HDL to provide this capability.

The 1020 Cable Driver consists of the following subsystems:

- PULSER: 5 nanoseconds rise time with peak amplitude continuously variable up to 200 amps

- TEST SECTIONS: 32-meter long cables, with or without connector assemblies

- INSTRUMENTATION HOUSING: 1-meter cube shielded box with connectors and adapters.

Direct Injection

Direct injection technology is used for threat and low-level system EMP assessment. A direct injection system creates a transient pulse on a system penetration by means of a point source or sources coupled to the penetration directly (resistance) or reactively (capacitance or inductance). This type of simulator is useful whenever other simulation techniques are inadequate or impractical from the standpoint of either peak amplitude or area of illumination.

The HDL has designed and built a variety of direct inject pulsers for specific applications. Some examples of direction injection pulsers are:

- 1 NANOSECOND PULSER - Rise time, 1 nanosecond, floating 600 nanosecond pulse into 50 ohms, voltage range 5-4000 volts.

- 5 NANOSECOND PULSER - Rise time, 5 nanosecond, single-ended 60-nanosecond pulse into 50 ohms, voltage range 7-900 volts.

- 1 MICROSECOND PULSER - Rise time, 1 microsecond, floating 60 microsecond pulse into 50 ohms, voltage range 500 to 5000 volts.

- 1 MILLISECOND PULSER - Rise time, 1 millisecond, floating 50-millisecond pulse into 50 ohms, voltage range 0-4000 volts.

Current Injection

The Maxwell Laboratories have developed a current injection simulator for DNA. The simulator is transportable and is housed in two, eight foot wide trailers designed for unrestricted road use. The simulator consists of two Marx generators (each 4Mj), one housed in each trailer. The two Marx generators are designed for parallel operation into a common load. A high-coulomb, rotating-arc, spark-gap switch is used in the pulsers. The pulser has an output voltage of approximately 320 kv, and delivers a millisecond current pulse to a nominal 20-ohm load. The pulser can drive time varying loads from high impedance to near short circuit. The simulator is a complete system and includes the necessary control, instrumentation and monitoring systems. Both 440 vac, three-phase, and 200 vac three-phase primary power must be supplied to operate the simulator.

PLACER

The Pulsed Loop Antenna Conduit Electromagnetic Radiator (PLACER) was developed by HDL. The transportable device is capable of detecting, locating, and measuring EM shielding flaws in buried conduits. It was designed for the SAFEGUARD Protection Integrity Maintenance Program. PLACER produces a pulsed electromagnetic field which induces current pulses onto buried conductors, and has been used to evaluate the RF integrity of buried conduit systems. Using the 30-kV version of PLACER, it is possible to determine the shielding effectiveness (to 80 dB) of conduits buried to a depth of 16 feet. By increasing the pulser voltage and the instrumentation sensitivity for monitoring currents on cables inside the conduit, it is possible to extend this dynamic range to more than 100 dB. Since the PLACER induced excitations are localized, it also is possible to determine the precise location of a conduit flaw. By complementing the PLACER field test results with laboratory flaw data, a threat analysis can be performed to determine system vulnerability.

The PLACER consists of the following subsystems:

- 0-40 kilovolts High Voltage Power Supply/Control Console
- 30-kilovolts Pulser and High Voltage Interconnect Cable
- 3-meter Diameter Loop Antenna
- Three-Wheel Cart.

7.2 DETECTING AND MONITORING EQUIPMENT

A variety of test instruments are used to detect, monitor, and record the signals sampled at various test points in a system under test. The types of instruments used include oscilloscopes, waveform recorders, spectrum analyzers, and field-intensity meters. Both pulsed and CW signals can be monitored and recorded in the time-domain with oscilloscopes and waveform recorders. Both pulsed and CW signals can be monitored and recorded in the frequency-domain with spectrum analyzers. Field-intensity meters and RF voltmeters are used primarily to monitor and record CW signals. The various types of instruments used in EMP hardness testing are described and discussed in more detail in the following sections.

7.2.1 Analog Oscilloscopes

The oscilloscope is an instrument that visually displays electrical signals against a time base on a cathode ray tube (CRT) and is used for time domain measurements. The analog oscilloscope utilizes linear amplifiers to display a continuous or sampled trace of the input signal. The digital oscilloscope, discussed in a later section, utilizes digital processing to generate the signal display on a cathode ray tube.

An elementary diagram of the analog oscilloscope is shown in Figure 7.2-1. The cathode ray tube displays the electrical signals as a visual image on a phosphorescent coating on the tube face. The image is created with a controlled beam of electrons emitted from a heated cathode. The electrons are accelerated and focused to create a spot on the CRT face, and the spot is moved by electrostatic forces on deflection plates. In most oscilloscopes, the two sets of deflection plates are located at right angles and a cartesian type display is utilized. One set of plates is used to control vertical deflection and the other controls horizontal deflection. When no voltage is applied to the deflecting plates, the electron beam passes between both sets of plates and appears as a bright spot on the CRT face. Usually, the voltage applied to the horizontal deflection plates has a sawtooth waveform that is proportional to time, permitting displays of vertical signal amplitude versus time. The sawtooth voltage waveform is normally generated by an internal timebase generator as shown in Figure 7.2-1. A trigger circuit is provided to control the sawtooth voltage in time relative to the signal under observation. The trigger establishes the time origin so that repetitive signals can be coherently superpositioned on the CRT display. The source of the trigger may be the signal under observation (internal), a signal external to the oscilloscope, or a 60 hertz power line. The internal trigger starts the sawtooth voltage after the onset of the signal under observation. The sawtooth voltage has some nonlinearity, particularly at the onset of the sawtooth voltage. Thus, with internal triggering, the initial portion of the waveform is lost and may possibly be distorted. This trigger problem can be overcome by adding a delay line in the vertical channel. For repetitive signals, the delay can be increased to a time slightly less than the signal period so that the sawtooth voltage can be started prior to the signal's next cycle.

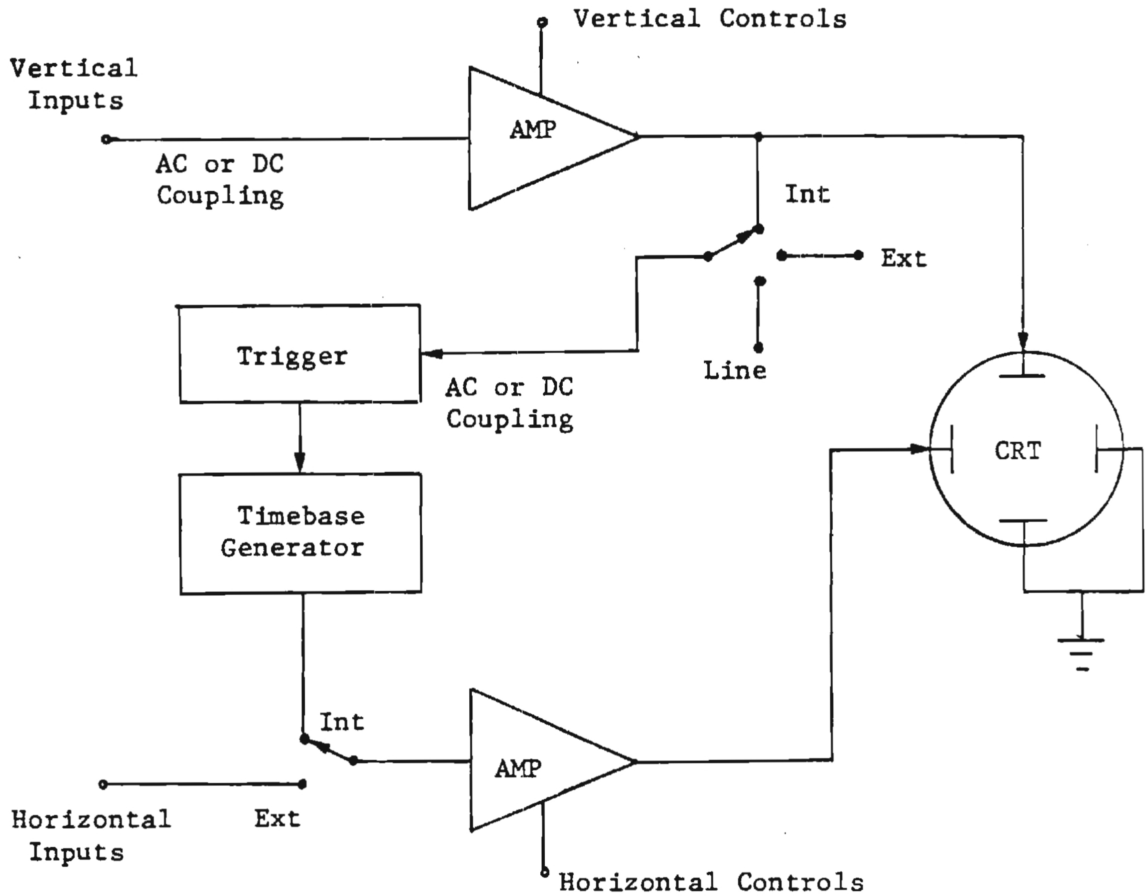


Figure 7.2-1. Analog Oscilloscope.

7.2.1.1 Basic Types of Analog Oscilloscopes. Oscilloscopes can be classified as one of three types: (1) general-purpose, (2) storage, and (3) sampling.

The general-purpose oscilloscope has no special features and is the oscilloscope most commonly found in the laboratory. The general-purpose oscilloscope cannot capture a signal and display it for long periods so that comparative measurements can be made. The storage oscilloscope has such capability. This type of oscilloscope is very similar to the general-purpose oscilloscope in all aspects except that a special CRT is used to store the signal image. Different types of storage CRT's are used. The bistable CRT uses electrically isolated phosphor dots on the CRT face, and dots have either a charged or uncharged state. Flood and writing guns in the CRT are used to charge the phosphor charge dots and display the signal image. The variable-persistence CRT has a storage mesh where a writing gun forms the signal image; thereafter, flood guns illuminate the phosphor where the storage mesh permits. The expansion CRT uses a miniature storage mesh with an electron lens system that magnifies and projects the storage image. An electron cloud from a flood gun projects the image through the electronic lens system into the CRT phosphor for viewing.

The response of a general-purpose oscilloscope is limited by the bandwidth of its vertical amplifier. Bandwidths of approximately 1 GHz can be achieved with the general-purpose oscilloscope. A sampling oscilloscope, on the other hand, can have bandwidths up to 18 GHz when low amplitude signals are sampled. The sampling oscilloscope operation depends on a sampling gate which uses a high-speed diode switch and a capacitor to store the sampled amplitude of an input signal. Progressive samples of the signal waveform are taken and then stretched in time, amplified by relatively low-bandwidth amplifiers, and finally displayed on a CRT as a series of dots that outline the signal image. The sampling oscilloscope is limited to depicting repetitive signals, since only a portion of the signal is captured and displayed each time the signal is repeated.

Multiple traces can be displayed on an oscilloscope and, depending on the method, oscilloscopes can be classified as dual-trace or multi-beamed. The general-purpose oscilloscopes may be either dual-trace or multi-beamed. The storage oscilloscope usually is dual-trace, while the sampling oscilloscope is usually only single channel. The dual-trace uses a single electron gun CRT, and multiple traces are obtained by switching between input signals, so that the input signals time-share the same electron gun. Two switching techniques are used: the chop mode and the alternate-mode. The chop-mode uses an electronic switch to display short segments of each input signal, and a vertical separation circuit generates an offset voltage to allow multiple trace display. In the alternate mode, input signal switching occurs at the end of each sweep. Multi-beamed oscilloscopes are required to view multiple one-shot phenomena or transient type signals. These oscilloscopes may be either: split-beam, dual beam, or dual gun. The split-beam oscilloscope has a single electron gun and uses a beam splitter to form two electron beams. Two sets of vertical deflection plates, and one set of horizontal deflection plates are used to control the electron beams. The dual-beam oscilloscope uses the same deflection plate configuration as the split-beam, but has two guns to generate the electronic beams. The dual-gun oscilloscope has two electron guns and two sets of vertical and horizontal deflection plates and functions essentially as two oscilloscopes in one. Transient signals can be displayed completely independent of each other using different timebases.

7.2.1.2 General-Purpose Oscilloscope Characteristics. Typical specifications for analog general purpose oscilloscopes are listed in Table 7.2-1. The deflection sensitivity, bandwidth, risetime, sweep-speed, and writing-speed are the specifications normally used to compare oscilloscope capabilities. The deflection sensitivity specification describes the input signal level needed to produce a stated deflection of the electron beam on the CRT. The bandwidth is the range of frequencies that an oscilloscope can display with less than 3-dB loss in amplitude, compared to the midband performance. The bandwidth is usually specified for the vertical channel, but can be specified for the horizontal channels and trigger circuits. Most oscilloscopes are designed so that a constant relates the bandwidth and rise time. This relationship is usually stated as:

$$T = \frac{0.35}{BW}$$

where T is the rise time and BW is the bandwidth. As an example, an oscilloscope with a bandwidth of 100 MHz has a rise time of 3.5 nanoseconds. The sweep-speed is the rate that the electron beam can be swept horizontally across the CRT. The writing-speed is the maximum rate at which the electron

TABLE 7.2-1

TYPICAL SPECIFICATIONS FOR ANALOG

GENERAL PURPOSE OSCILLOSCOPES

PARAMETER	SPECIFICATION RANGE
Voltage Range	10 μ V - 100 V
Deflection Sensitivity	10μ V/Div - 20 mV/Div
Bandwidth Vertical Channel Horizontal Channel	 DC - 1 GHz DC - 350 MHz
Vertical Channel Risetime	350 ps - 85 μ s
Sweep Speed	1 ns/Div - 100 s/Div
Writing Speed	.5 cm/ns - 20 cm/ns
Vertical Amplitude Accuracy	.1 - 5 %
Typical Suppliers	
Tektronix	Beaverton, Oregon
Hewlett-Packard	Palo Alto, California
Gould	Santa Clara, California
Nicolet Instrument	Madison, Wisconsin

beam can be moved across the CRT and still produce a visible trace. The writing-speed is dependent on the CRT's phosphor and its electronics. Other specifications such as display spot size, trace width, resolution, and slewing rate should be considered when recording transient data via oscilloscope cameras. These specifications are not always available from oscilloscope manufacturers. The display spot size is dependent on the electron beam diameter and the CRT phosphor. The tracewidth is the minimum width of the signal trace. Resolution is defined as the number of tracewidths that can be displayed. Slewing rate depends on the oscilloscope writing speed and the rise time capability of the oscilloscope electronics.

7.2.2 Digital Oscilloscopes and Waveform Recorders

Waveform recorders and digital oscilloscopes both use digital processing to measure signal characteristics. Both instruments are very similar in their operation. The digital oscilloscope is more a stand-alone instrument in that it has a built-in display and may provide on-board processing of signals. The waveform recorder, which is also called a waveform digitizer, usually lacks an integral display and is intended to be interfaced with a computer that processes the digital data. The waveform recorder often has an analog-to-digital converter with higher resolution and sampling rates as compared to the digital oscilloscope. The terminology, waveform analyzer, is often used in regard to a waveform recorder. In actuality, a waveform analyzer may be one of many types of equipment, including a spectrum analyzer, a network analyzer, or an audio distortion meter.

Figure 7.2-2 shows the general configuration of a digital storage oscilloscope. The instrument's timing is controlled by a time base generator and a precise digital clock, which controls the digital processing and the control of the CRT. The input analog signal is sampled using an A/D converter that transforms sampled levels into binary numbers or data words. The data words are stored in a digital memory where they can be retrieved for display at a rate best suited for analysis. The output of the digital storage memory is converter back to analog through a D/A converter, and the analog signals are displayed on the CRT using a timebase. The digital oscilloscope has several advantages over the analog oscilloscope. The real-time sampling techniques used by digital oscilloscopes permit capture of both repetitive

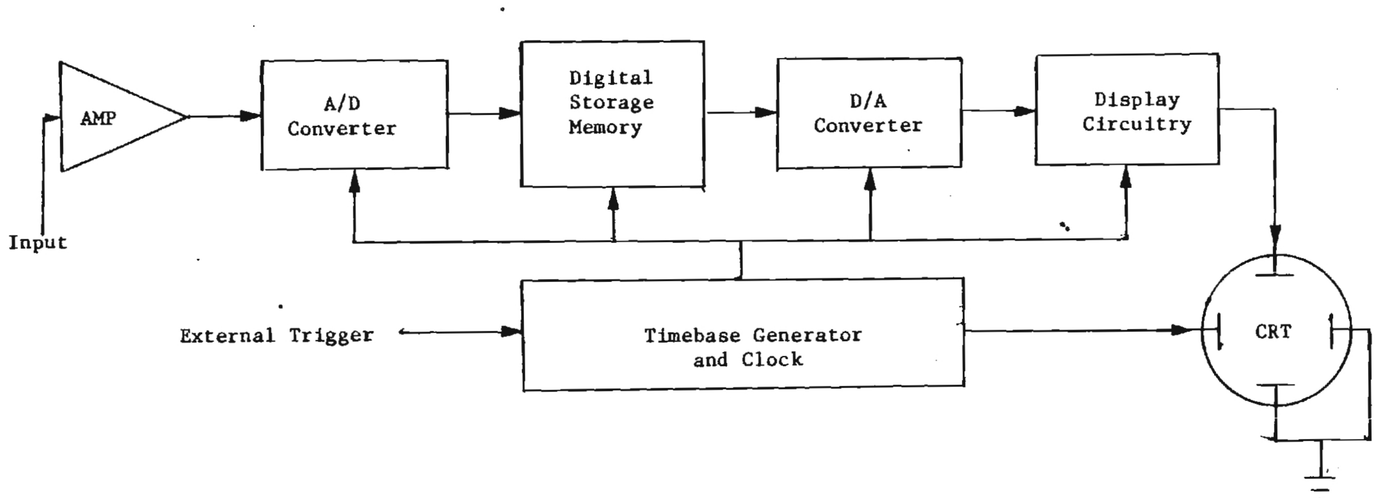


Figure 7.2-2. Digital Storage Oscilloscope.

and single-shot signals. In contrast, the analog sampling oscilloscopes use a non-real-time sampling technique, such as sequential and random, and can capture only repetitive signals. Analog storage scopes can capture and display transient waveforms for a limited period of time. However, to obtain a clear trace, the operator must perform many adjustments. Even after a clear trace is obtained, a permanent record of the waveform must be made with a camera and data must be scaled from photographs for use in computer analyses. Another advantage of a digital oscilloscope is its ability to store many waveforms, and retrieve the waveforms for later analyses. The pretrigger viewing feature of digital scopes provides another advantage. Because the trigger point is only a reference point within the digital memory and not the first data point acquired, information before and after the trigger point is stored and available to the user.

The configuration of the waveform recorder is shown in Figure 7.2-3. As previously noted, its operation is similar to that of the digital oscilloscope. The difference between the two instruments is more in application than hardware. The waveform recorder is specifically designed to interface with a computer and does not have a CRT. Both analog and digital outputs are available from the waveform recorder.

Table 7.2-2 lists some of the typical parameters and specifications for digital oscilloscopes and waveform recorders and several typical suppliers.

7.2.3 Spectrum Analyzers

A spectrum analyzer is an instrument used to graphically present voltage or power as a function of frequency on a display such as a cathode ray tube. An oscilloscope displays the sum of a signal's frequency components against a timebase and thus is said to be working in the time domain. By contrast, a spectrum analyzer displays the individual frequency components of the signal and presents their related voltage or power levels. The spectrum analyzer has certain advantages not found in an oscilloscope and is particularly suited for wide dynamic range measurements, low-level signal distortion measurements, modulation measurements, frequency stability measurements, and frequency response measurements.

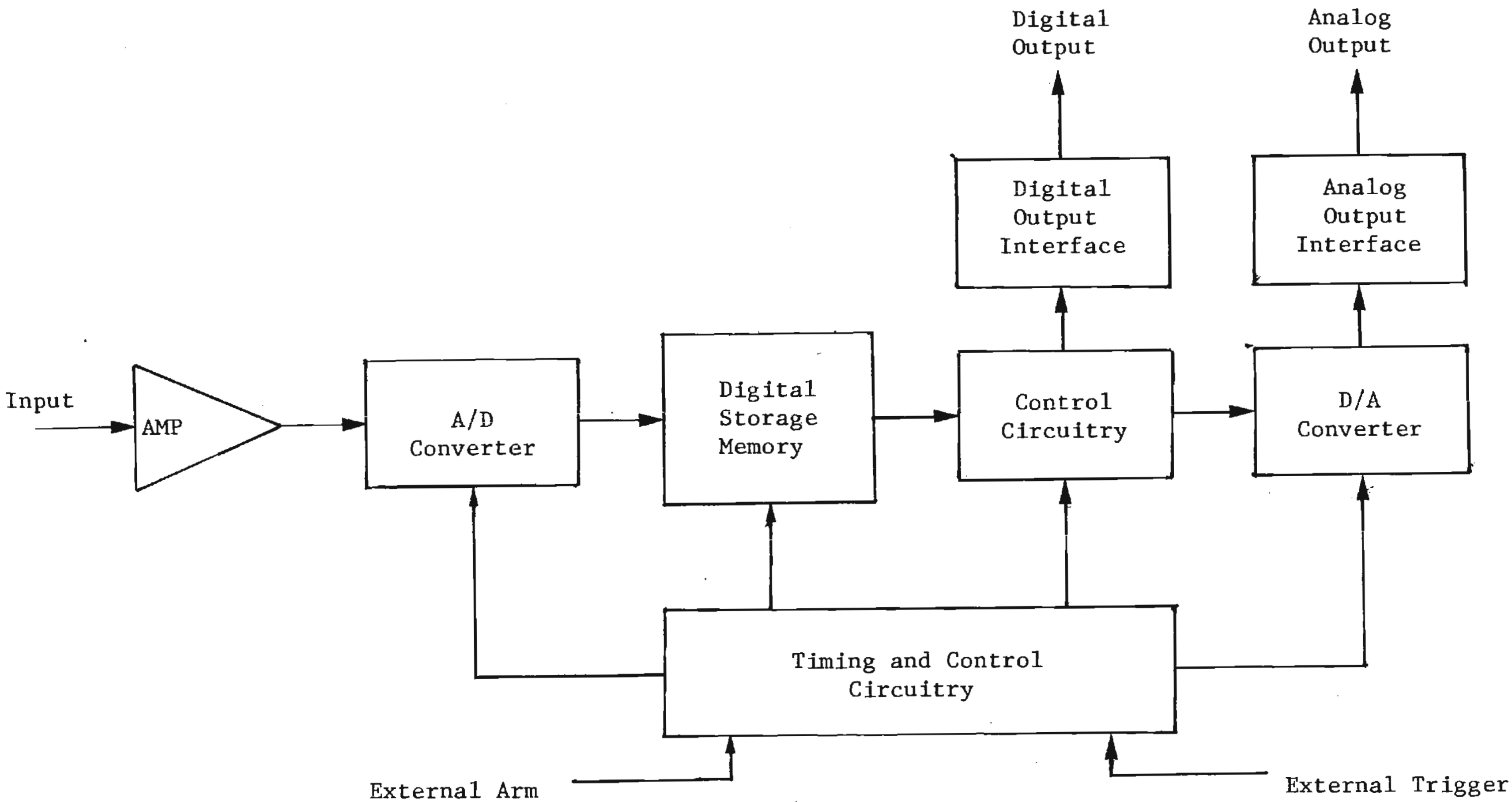


Figure 7.2-3. Waveform Recorder.

TABLE 7.2-2

TYPICAL SPECIFICATIONS FOR DIGITAL
OSCILLOSCOPES AND WAVEFORM RECORDERS

PARAMETER	SPECIFICATION RANGE
Digital Channels	1-4
Analog Input Bandwidth	100 KHz - 1 GHz
Maximum Digitizing Rate	100 KHz - 400 MHz
Maximum Resolution	8-15 bits
Memory Length (words)	1-128 K
Interface	IEEE - 488 Programmable Control
Typical Suppliers	
Hewlett-Packard	Palo Alto, California
Tektronix	Beaverton, Oregon
Gould-Biomation	Santa Clara, California
Nicolet Instrument	Madison, Wisconsin
Norland	Ft. Atkinson, Wisconsin

7.2.3.1 Basic Types of Spectrum Analyzers. There are two basic types of spectrum analyzers; real-time and nonreal-time. A real-time spectrum analyzer simultaneously displays the amplitude of all signals in its frequency range and thus preserves the time dependency between signals which permits phase information to be displayed. A real-time spectrum analyzer is capable of analyzing a signal within its frequency coverage in τ seconds with a resolution of $1/\tau$, and thus can display transient responses as well as periodic and random signals. The nonreal-time spectrum analyzer samples the spectrum sequentially in time, and the signal must be repetitive to determine the complete spectrum. The real-time spectrum analyzer can analyze signals with frequencies in the kilohertz range, while the nonreal-time spectrum analyzers can analyze signals in the high gigahertz range.

Real-time spectrum analyzers may be either: (1) a multiple-filter analyzer, (2) a digital fast-Fourier-transform analyzer, or (3) a time-compression spectrum analyzer. Figure 7.2-4 shows the configuration for a multiple-filter, real-time spectrum analyzer. This analyzer uses a bank of staggered bandpass filters. The composite amplitude of the signals within each filter passband is displayed as a function of the combined filter output. The output of each filter channel is proportional to the amplitude of the frequency component within its bandpass. The time constant of each filter is the reciprocal of its bandwidth. Since each filter channel contains its own detector, the output of the entire filter bank may be scanned as fast as necessary. In fact, it is possible to scan the entire filter bank in the time constant of one filter, and thus operate in real time. The multiple-filter analyzer can provide very good spectral resolution since the bandpass of the filters can be very narrow. However, its frequency range is limited by the number of filters and their bandwidth.

The digital fast-Fourier-transform analyzer configuration is similar to the multiple-filter analyzer. The Fourier analyzer uses digital filters in place of the bank of parallel filters, and it uses the Discrete Fourier Transform which employs a highly efficient algorithm known as the Fast Fourier Transformer. This algorithm calculates the magnitude and phase of each spectral component from a block of time domain samples of the input signal. The Fourier analyzer is well suited for the measurement of random signals obscured by noise, the statistical properties of signals, very low frequencies, or closely spaced signals.

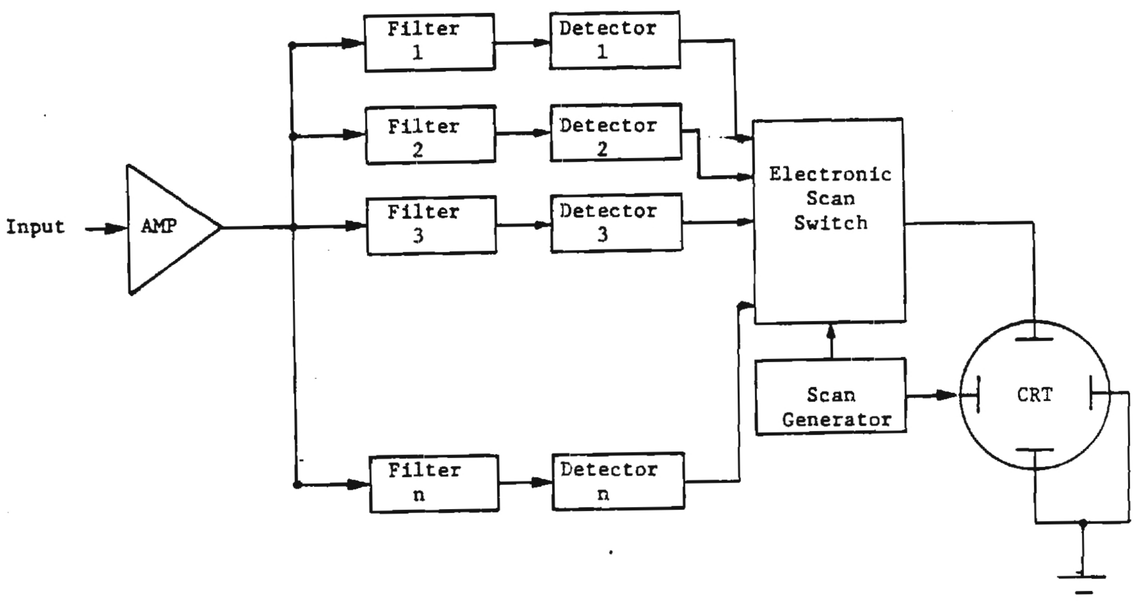


Figure 7.2-4. Multiple-filter Real-time Spectrum Analyzer.

The basic components of the time-compression, real-time spectrum analyzer are shown in Figure 7.2-5. The time-compression spectrum analyzer compresses the time base of the input signal, thus expanding its spectrum and permitting it to be analyzed at very fast rates. The input signal is sampled with an analog-to-digital converter, and the digitized samples are passed into a recirculating digital memory. (The sampling rate is determined by the frequency range over which the analyzer is operating.) The sampled digital data emerging from the memory output are fed back into the memory input. These samples are sequenced with the latest input samples so that the memory contains all the samples in their order of arrival. Thus, the time interval between successive digitized samples that emerge from the memory is extremely short compared to the interval between samples of the input analog signal. This speed up contracts the signal's time base. The output of the digital memory is fed to a digital-to-analog converter. The ouptut of the converter is an accelerated version of the original input signal. After filtering this output, the analog signal is analyzed using nonreal-time spectrum analysis techniques. The digital memory gives the time-compression analyzer the capability to capture or to take a snapshot of one-shot transients or selected segments of continuous signals since the signal is circulating in the memory. In this respect, the time compression analyzer behaves very much like a tape loop.

Nonreal-time spectrum analyzers are usually of the TRF (tuned radio frequency) or superheterodyne configuration. As shown in Figure 7.2-6, the TRF analyzer consists of a bandpass filter whose center frequency is tunable over a desired frequency range, a detector, a sweep generator, and a CRT to display the signal being analyzed. Because the TRF analyzer has a tunable filter it is limited in sweep width depending on the frequency range. The analyzer's resolution is determined by the filter bandwidth. Since tunable filters do not usually have constant bandwidth, the resolution is dependent on frequency. A wave analyzer, which may also be referred to as a frequency selective voltmeter or carrier frequency voltmeter, is a form of a TRF analyzer.

The most common nonreal-time spectrum analyzer uses a swept-frequency technique where the spectrum is swept through a fixed bandpass filter instead of sweeping a filter through the spectrum (i.e., the TRF analyzer). The swept-frequency analyzer is essentially a superheterodyne receiver with a

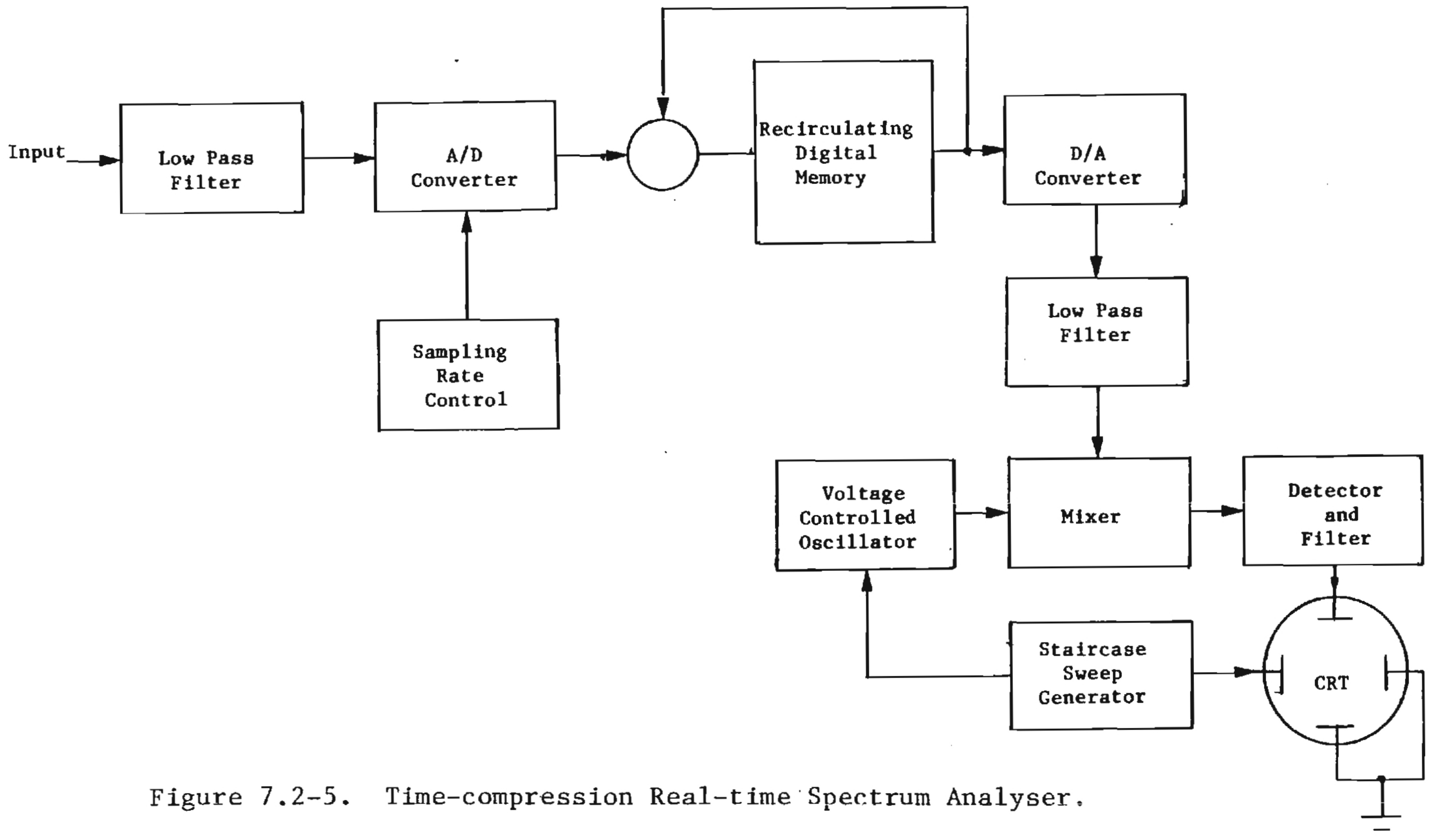


Figure 7.2-5. Time-compression Real-time Spectrum Analyser.

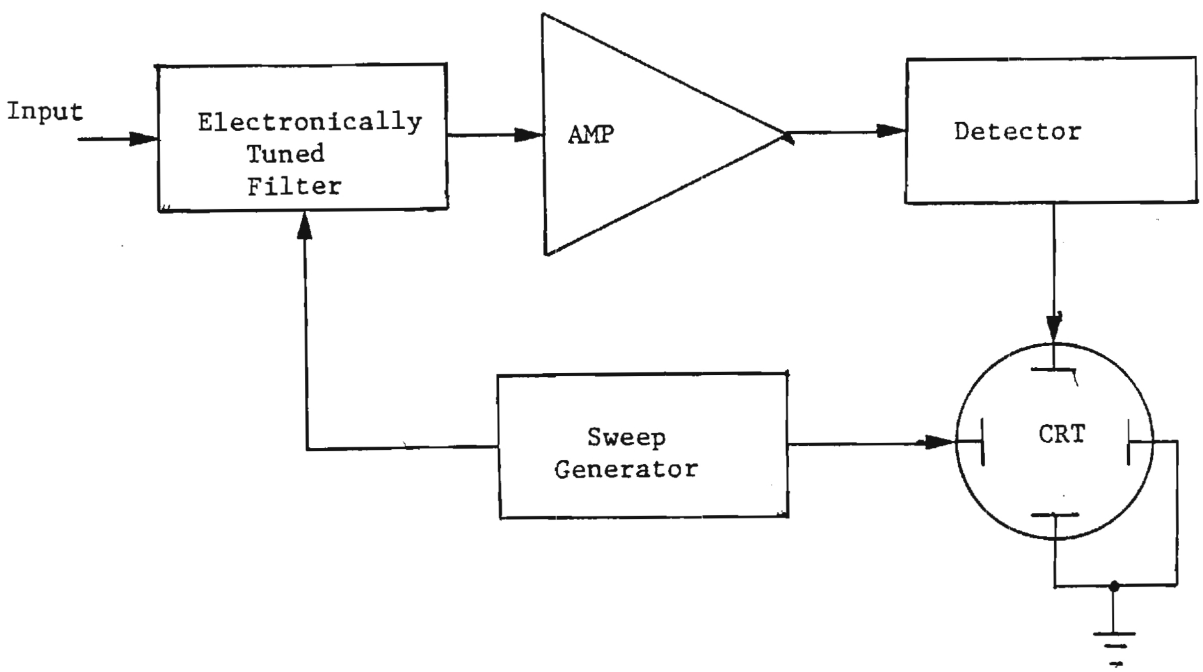


Figure 7.2-6. Swept TRF Spectrum Analyzer.

broadband input and a swept-frequency local oscillator. This arrangement is most suitable for obtaining both large bandwidth and wide dynamic range capabilities. The swept-frequency analyzers may use either the swept-IF or swept-front-end configuration. The swept-IF analyzer shown in Figure 7.2-7 is used when high resolution is required. This configuration has the advantage that the swept local oscillator for the second mixer is at a lower frequency and improved swept-frequency operation is more attainable. The greatest limitation of this configuration is the observable spectral width (dispersion), which is determined by the bandwidth of the first IF amplifier. Thus, the dispersion is limited to several hundred megahertz. The swept-front-end analyzer shown in Figure 7.2-8 is usually used when a wide dispersion is required with moderate resolution. Both of the swept-tuned spectrum analyzers are basically narrowband receivers that are electronically tuned in frequency by applying a saw-tooth voltage to a voltage tuned local oscillator. This same saw-tooth voltage is simultaneously applied to the horizontal deflection plates of the CRT to form the frequency baseline. The output from the detector is synchronously applied to the vertical deflection plates of the CRT, and a graph of amplitude versus frequency is displayed.

<u>7.2.3.2 Spectrum Analyzer Characteristics</u>. The real-time spectrum analyzer can capture and analyze transients or random signals by simultaneously displaying all frequency components, thus preserving phase information. Real-time spectrum analyzers are used to analyze signals having components within the 0 to 100 kHz frequency range. Resolutions in the millihertz range can be achieved, and dynamic ranges of 70 dB are typical. The input impedances are generally high and on the order of one megohm. Both log and linear display modes are available. Typical suppliers of real-time spectrum analyzers are: Hewlett-Packard, Palo Alto, California; Nicolet Instrument Corporation, Northvale, New Jersey; Wavetek, Rockleigh, New Jersey; and Spectral Dynamics, San Diego, California.

Table 7.2-3 presents the typical specification range for swept-spectrum analyzers. This type of analyzer is commonly used for CW type EMP measurements. General capabilities desired in these analyzers are:

- Flat frequency response so that amplitude is independent of frequency
- Calibrated in both frequency and amplitude for relative and absolute measurements

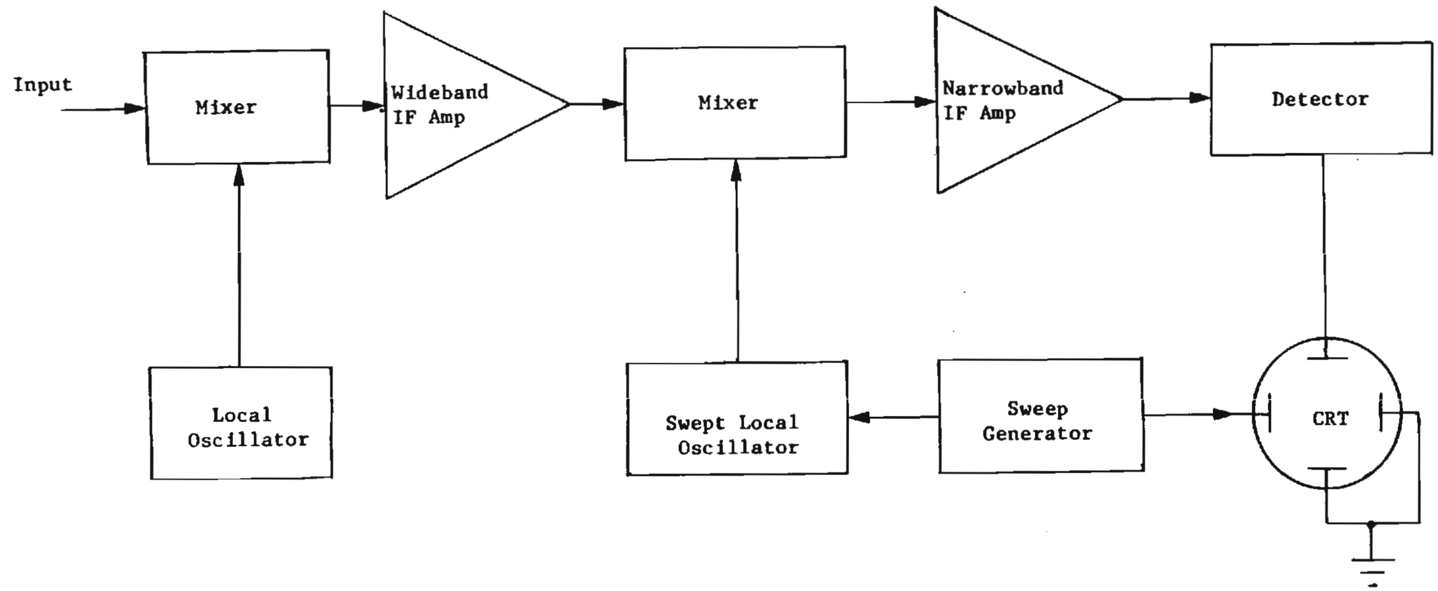


Figure 7.2-7. Swept-IF Spectrum Analyzer.

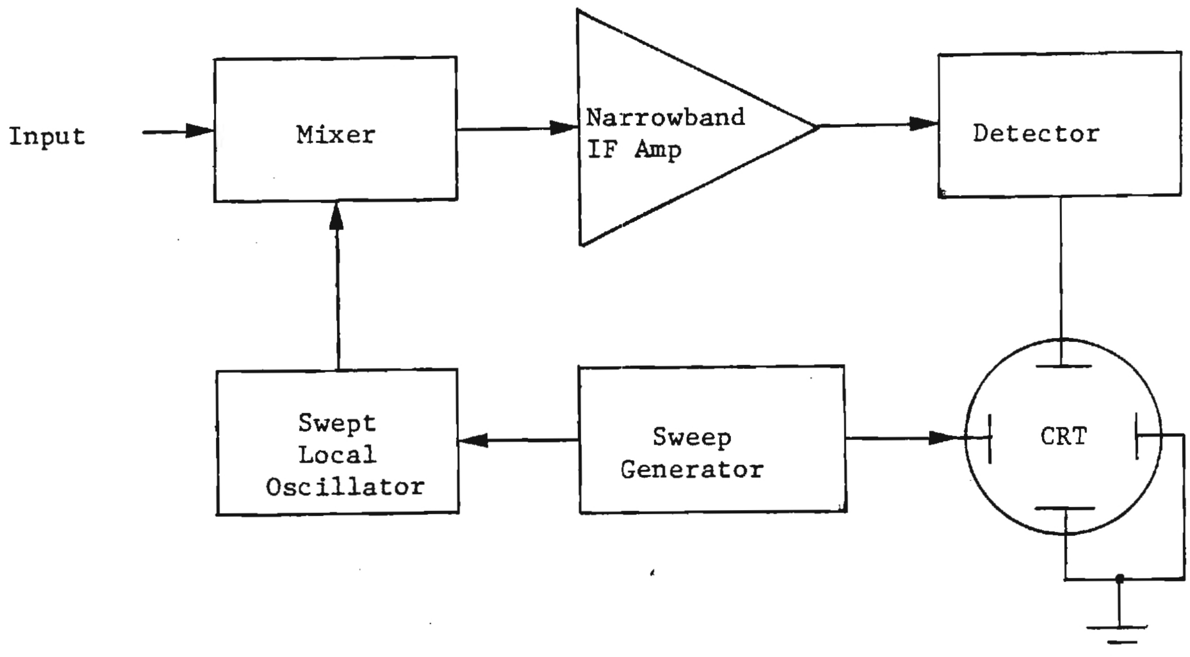


Figure 7.2-8. Swept-front-end Spectrum Analyzer.

TABLE 7.2-3

TYPICAL CHARACTERISTICS OF SWEPT-SPECTRUM ANALYZERS

PARAMETER	SPECIFICATION RANGE
Frequency Range	10 Hz to 60 GHz 220 GHz with external mixing
Narrowest Resolution	3 Hz to 10 KHz
Sensitivity	-130 to -90 dBm
Maximum Input Signal	+ 15 to + 30 dBm
Amplitude Accuracy	± .2 to ± 2 dB
Screen Dynamic Range	80 - 100 dB
Input Impedance	50 Ω 1 MΩ
ATE Capability	IEEE-488 Compatibility Full Program Control
Weight	40 - 110 lbs.
Power Consumption	150 - 650 watts
Typical Suppliers	
Hewlett-Packard	Palo Alto, California
Tektronix	Beaverton, Oregon
Eaton Alltech	Ronkonkoma, New York
Electro-Metrics	Amsterdam, New York
Marconi	Northvale, New York
Polarad	Lake Success, New York
Texscan	Indianapolis, Indiana

- An indicator to show when the analyzer is in an uncalibrated mode
- Good frequency stability and high resolution
- High sensitivity to measure low-level signals
- Wide dynamic range, both signal range and on-screen display
- Linear and logarithmic display modes

Swept-spectrum analyzers do have potential measurement problems that must be considered. If the signal of interest is swept too fast through the IF of the spectrum analyzer to accommodate the response time of the bandpass filter, the level displayed will be incorrect. The sweep time, bandwidth, and frequency range must be compatible to prevent such incorrect indications. Most of the newer spectrum analyzers have an indicator light to show when the display is not calibrated. Spectrum analyzers also tend to have low sensitivity (as compared to a field intensity meter) due to high noise figures, but its sensitivity can be improved by using a low noise figure preamplifier. The preamplifier may limit the frequency range of the analyzer, and several preamplifiers may be required. A signal level may also be displayed incorrectly if the signal level at the input mixer is too high, causing gain compression. RF attenuation should be added to decrease the signal level until the decrease in the displayed signal amplitude tracks the change in attenuation. Swept-spectrum analyzers generally do not have a built-in RF tracking preselector, particularly for frequencies below 1 GHz. If several large signals are present in the RF passband of an analyzer, an overload condition may occur and distortion products can be generated. The input to swept-spectrum analyzers must be limited, since the input attenuators and mixers are easily damaged if design limits are exceeded.

7.2.4 Field Intensity Meters

A field intensity meter is basically a superheterodyne receiver which has an internal calibrator and special detector circuits to measure and calibrate, in the frequency domain, the voltage amplitude of signals. Other distinguishing features are built-in RF preselectors, attenuators, and a shielded instrument case. The field intensity meter may be used as a stand-alone instrument, or as a part of an automated test system. Field intensity meters that operate from 115 vac or from internal rechargable batteries are available.

A typical field intensity meter configuration is shown in Figure 7.2-9. The input attenuator permits measurements over a wide range of inputs, and the attenuator may be a three- or four-decade step attenuator. The calibrator may have an internal sine wave source that is tracked to the tuned frequency or may have an impulse source to calibrate across the band without tuning. The preselector may be a tunable RF amplifier or may be electronically or mechanically tuned filters. The preselector function is to attenuate high-level, out-of-band signals which may cause signal distortion or incorrect measured data. The IF amplifier stage usually includes an IF attenuator which may be ganged with the input attenuator. The bandwidth of the instrument is determined by the IF amplifier stage response and the bandwidth is changed by selecting different circuit components or filters. The detector and weighting circuits provide different detection functions. A peak function measures the peak amplitude of the IF amplifier output, and is used to measure the peak of pulsed or impulsive type signals. A quasi-peak detector has a time constant chosen to make measurements that depend on both amplitude and time distribution. The average detector function, also referred to as the field-intensity detector, has a detector followed by an averaging network. This detector function measures the average envelope of signals at the output of the IF amplifier.

Typical characteristics of commercially available field intensity meters and several typical suppliers are listed in Table 7.2-4.

7.3 SPECTRAL NETWORK ANALYZERS

Network analyzers are exteremely versatile tools which can be used to quickly and easily determine the transfer and/or impedance characteristics of linear devices through CW frequency testing. A network analyzer system consists of several components which can be configured around the device under test in different ways to accomplish the desired measurement. The first requirement of the system is a CW signal source to stimulate the device under test. Since transfer and impedance functions are ratios of various voltages and currents, a means of separating the appropriate signals from the measurement ports of the device under test is required. Finally, the network analyzer detects the separated signals, forms the desired ratios, and displays the results.

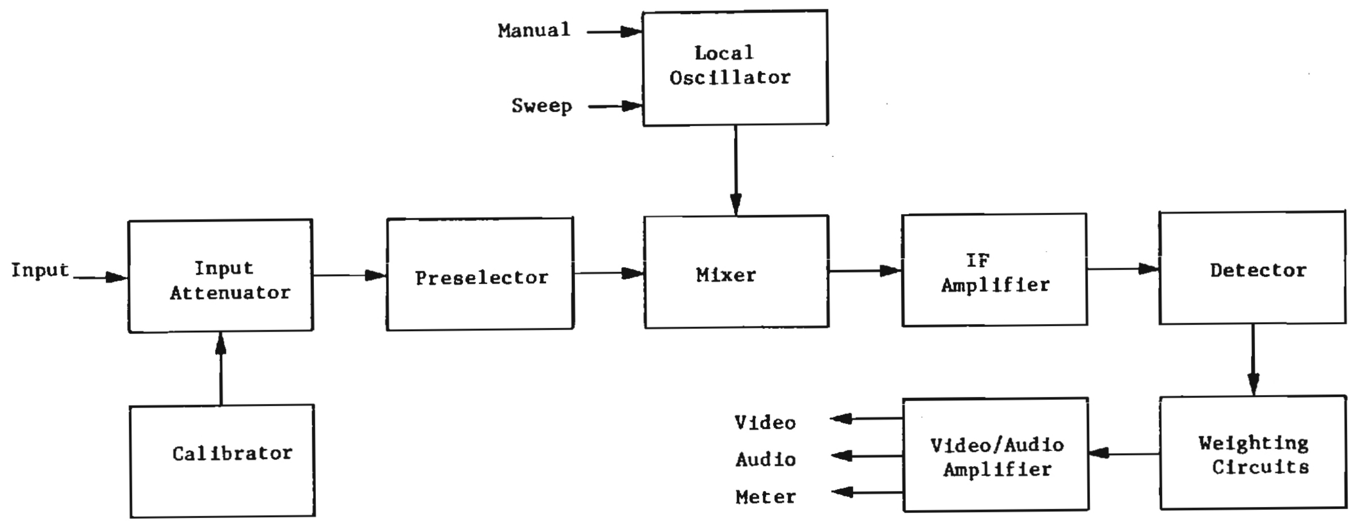


Figure 7.2-9. Field Intensity Meter Configuration.

TABLE 7.2-4

CHARACTERISTICS OF FIELD INTENSITY METERS

PARAMETER	SPECIFICATION RANGE
Frequency Range	20 Hz to 40 GHz
Narrowband Sensitivity	-143 to -80 dBm
Noise Figure	3 to 40 dB
Accuracy	± 2 dB typical
Bandwidths	100 Hz to 1 MHz
Input Impedance	50 ohms nominal
Spurious Response	40 - 70 dB minimum
Detectors	Average, Peak, Quasi Peak
Case Shielding	80 dB minimum
Size	10"H X 19"W X 20"D Typical
Weight	25 - 75 lbs. typical
Power Source	115 Vac or Battery
Typical Suppliers	
Eaton Ailtech, Ronkonkoma, New York Electro-Metrics, Amsterdam, New York Electro-Mechanics, Co., Austin, Texas Rohde & Schwartz, Lake Success, New York	

Generally, network analyzers are capable of swept measurements and utilize sweep generators to stimulate the device under test. This allows quick and easy characterization of devices over broad frequency ranges. Although some network analyzers will operate only with a companion source, any CW source or sweeper meeting the network analyzer's specifications can generally be used to stimulate the device under test. For a complete discussion of CW generators and sweepers, see Sections 7.1.1 and 7.1.2 of this handbook.

At low frequencies, it is not particularly difficult to separate the appropriate voltages and currents required for transfer and impedance function measurements. Signal separation is the process of establishing the proper shorts, opens, and connections at the measurement ports of the device under test. As the frequency increases, the problem of signal separation usually involves traveling waves on transmission lines and becomes correspondingly more difficult. The three most commonly used devices for signal separation in high-frequency swept measurements are: directional couplers, directional bridges, and power splitters.

Typically, network analyzers utilize broadband detection techniques which accept the full frequency spectrum of the input signal. However, some analyzers use narrowband detection which involves tuned receivers to convert CW or swept RF signals to a constant IF signal. Broadband systems are generally source independent while narrowband systems require companion tracking sources which both stimulate the device under test and act as the analyzer local oscillator. Broadband detection reduces instrument cost, but sacrifices noise and harmonic rejection. However, noise is not a factor in typical EMP applications, and the use of appropriate filters will eliminate harmonic signals that would otherwise preclude accurate measurement.

Once the RF has been detected, the network analyzer must process the detected signals and display the measured quantities. All network analyzers are multi-channel receivers utilizing a reference channel and at least one test channel. Absolute signal levels in the channels, relative signal levels (ratios) between channels, and relative phase differences between channels can typically be measured. Using these measured quantities, it is possible to either display directly or compute the magnitude and phase of transfer or impedance functions. Swept frequency measurements of amplitude and phase are usually displayed on CRT screens versus frequency or on X-Y recorders. Most network analyzers include a digital storage medium that allows for the "memorization" of system residuals, needed in the normalization or calibration procedure prior to the testing of the device under test. The subtraction of these system residuals by means of input-minus-memory results in a swept response display that is virtually free of any frequency-related idiosyncrasies inherent in the measurement system itself.

The computational capabilities of a digital computer complement the versatility of modern network analyzers. Computer controlled network analyzers can be programmed to perform many measurements automatically, with operators required only to set up and initiate the tests. The measurement process is further accelerated by the computer's ability to store, transform, summarize, and output the data in a variety of formats. Most errors in network measurements are complex quantities that vary as a function of frequency, making manual error correction prohibitive. However, the computer can greatly enhance measurement accuracy by quickly and easily performing complex computations for sophisticated error correction.

In order to cover the 100 Hz to 1 GHz frequency range required for EMP hardness and maintenance testing, the use of a low-frequency network analyzer and a high-frequency network analyzer will be required. At low frequencies (less than 10 MHz), network analyzers generally characterize the device under test by measuring the gain/loss and phase changes through the device and its associated input and output impedances. Lumped component models such as h, y, and z parameters are typical analytical and computational tools used to represent these measurements and some low-frequency network analyzers measure these parameters directly.

Measurement of voltages and currents become more difficult as frequency increases. Consequently, h, y, and z parameters loose their usefulness at high frequencies. High frequency network behavior can be better described using transmission line theory in terms of forward and reverse traveling waves. Scattering or S-parameters were developed to characterize linear networks at high frequencies. Some network analyzers measure and directly display S_{12} or S_{21} as gain or attenuation and S_{11} or S_{22} as reflection coefficient, return loss, or impedance. Table 7.3-1 shows typical parameters of commercially available network analyzers and their measurement capabilities.

TABLE 7.3-1

TYPICAL PARAMETERS AND MEASUREMENT CAPABILITIES OF

COMMERCIALLY AVAILABLE NETWORK ANALYZERS

TYPE	FREQUENCY RANGE	DYNAMIC RANGE	CHANNELS	MEASUREMENT CAPABILITIES
Low Frequency	50 Hz - 13 MHz	100 dB	A,B	Gain or Insertion Loss Phase Shift Complex Impedance h, y, z parameters
High Frequency	10 MHz - 18 GHz	80 - 100dB	A,B,R	Complex Transfer Function Complex Impedance S parameters

Typical Network Analyzer Suppliers	
Anritsu America, Inc.	Oakland, New Jersey
General Microwave Corporation	Farmingdale, New York
Hewlett Packard Co.	Palo Alto, California
Polarad Electronics Inc.	Lake Success, New York

Figure 7.3-1 shows a typical test setup for a swept frequency complex transfer function measurement. The setup is calibrated by removing the device under test, connecting the two cables in the test input channel, and measuring the amplitude and phase differences between the test and reference inputs. These results are then subtracted either manually or automatically from the results measured with the device under test. Figures 7.3-2 and 7.3-3 show typical test setups for swept frequency complex impedance measurements using low-frequency and high-frequency network analyzers, respectively. Low-frequency analyzers utilize voltage and current ratios to determine complex impedance while high-frequency analyzers utilize forward and reflected wave analysis to determine complex impedance. Calibration for both test setups is performed by replacing the device under test with a 50-ohm or other appropriate load.

7.4 CONTINUITY MEASURING EQUIPMENT

Continuity tests are an important part of any EMP hardness maintenance and surveillance program. These tests are performed to evaluate the quality and integrity of cable shields, shield splices, connectors, welded seams, bonds, and ground connections. These measurements are normally performed with a low-resistance ohmmeter. These instruments are capable of measuring resistance values down to 1 micro-ohm. The instruments are four-terminal devices that use a Kelvin connection to prevent the resistance of the test leads from affecting the accuracy of the measurement. Instruments are commercially available with either digital or analog direct reading output displays.

Typical characteristics of commercially available low resistance ohmmeters and several typical suppliers are listed in Table 7.4-1.

7.5 ANTENNAS

The use of antennas as both radiators and receptors is required in the performance of some hardness maintenance and surveillance tests and inspections. The broad frequency range over which these tests must be performed dictates that different types of antennas be used to satisfy all the requirements.

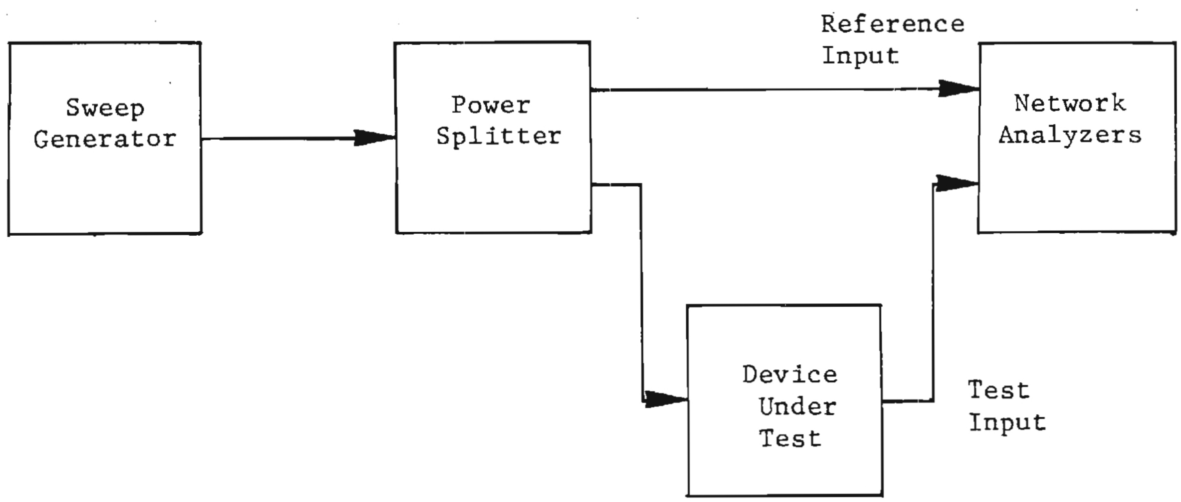


Figure 7.3-1. Swept Frequency Transfer Function Test Setup.

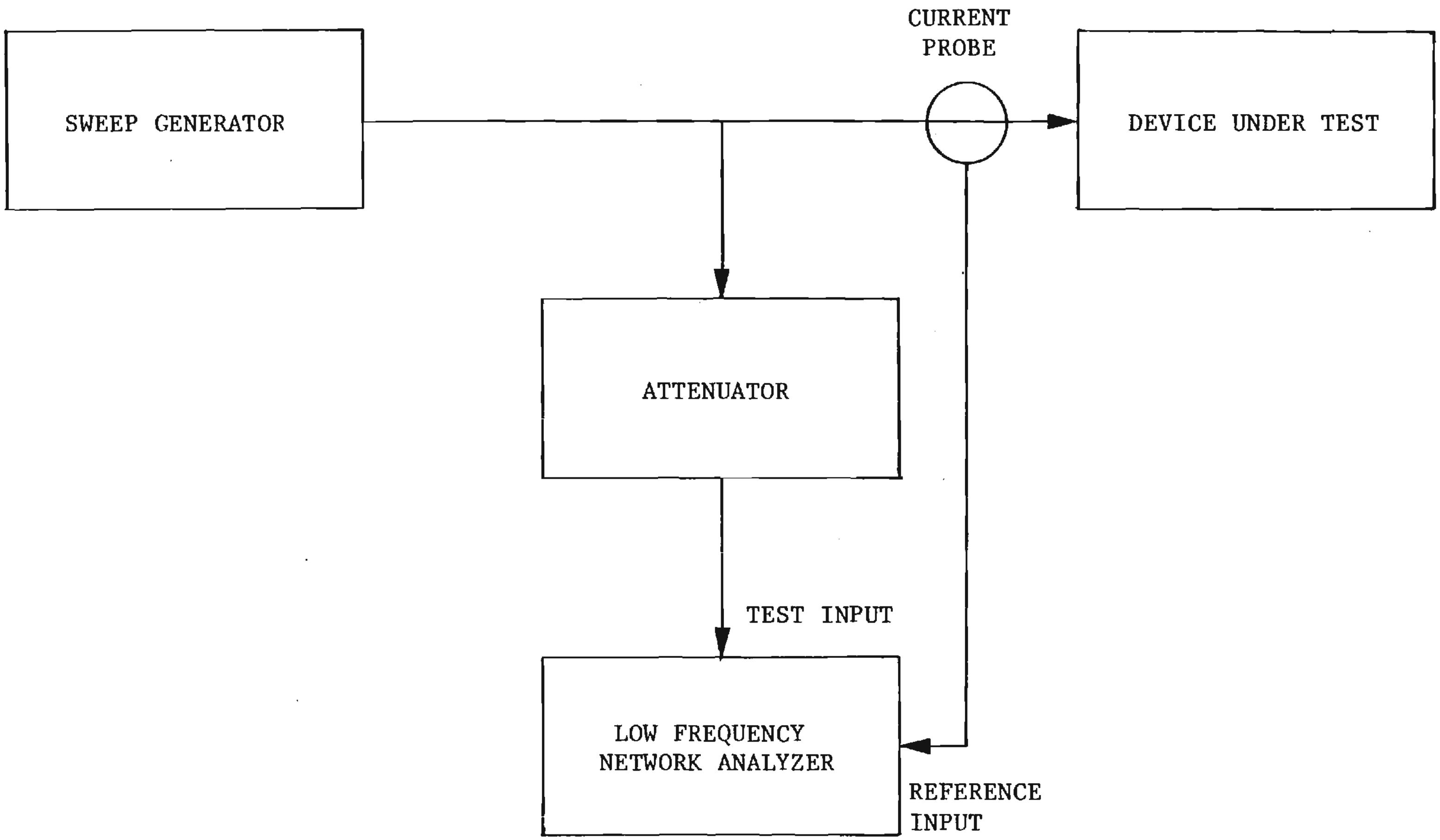


Figure 7.3-2. Swept Frequency Impedance Measurement Test Setup Using Low Frequency Network Analyzer.

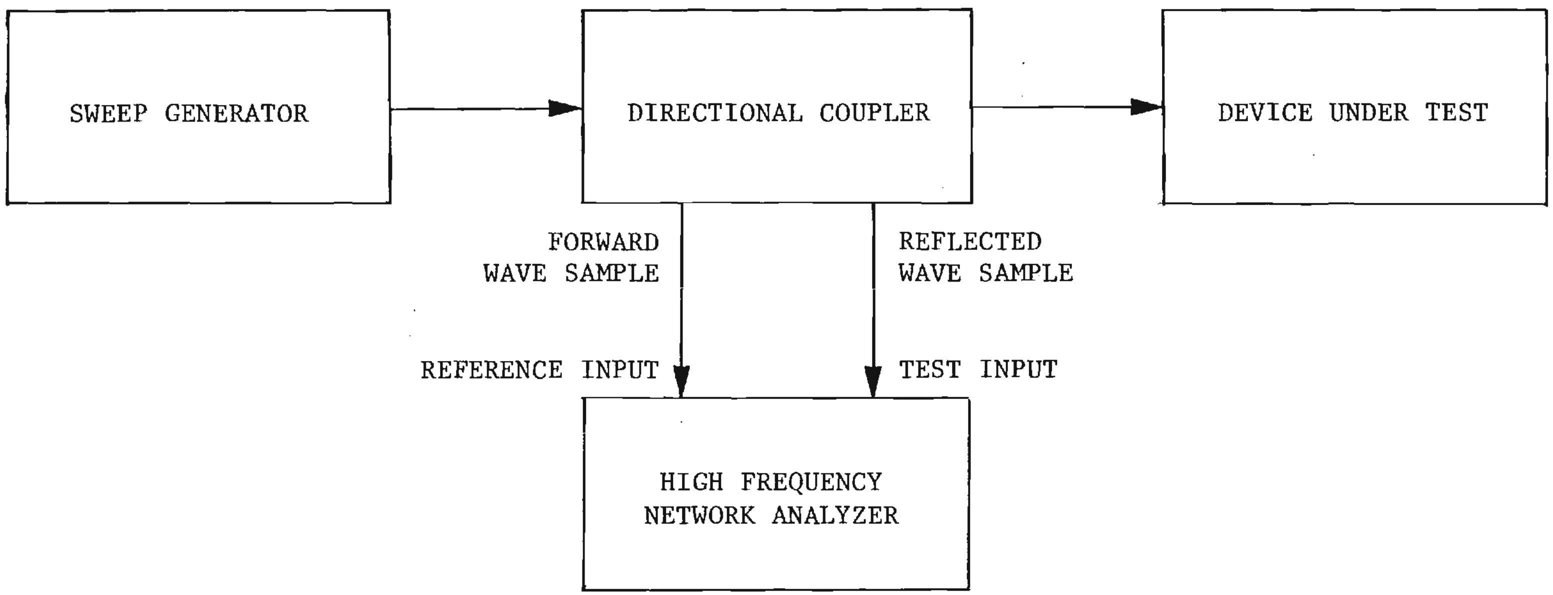


Figure 7.3-3. Swept Frequency Impedance Measurement Test Setup Using High Frequency Network Analyzer.

TABLE 7.4-1

TYPICAL CHARACTERISTICS OF COMMERCIALLY AVAILABLE LOW RESISTANCE OHMMETERS

TYPE	SENSITIVITY	RANGE	ACCURACY
HIGH SENSITIVITY	0.2μΩ	0.2μΩ - 20Ω 6 BANDS	1/2% READING
MEDIUM SENSITIVITY	1μΩ	1μΩ - 20 Ω 5 BANDS	1/4% READING
LOW SENSITIVITY	100μΩ	100μΩ - 5Ω 6 BANDS	5% FULL SCALE

TYPICAL LOW RESISTANCE OHMMETER SUPPLIERS

BIDDLE INSTRUMENTS	BLUE BELL, PA
HEWLETT-PACKARD	PALO ALTO, CA
JOHN FLUKE MFG. CO., INC.	EVERETT, WA
SHALLCROSS	SELMA, NC

7.5.1 Loop Antennas

Loop antennas are normally used as radiators and receptors in the frequency range from 100 Hz to 30 MHz. At least two different size loop antennas are required to cover this frequency range. Loop antennas for use over the 20 Hz to 50 KHz and 10 KHz to 30 MHz frequency ranges are commercially available.

7.5.2 Dipole Antennas

Dipole antennas are normally used as radiators and receptors in the frequency range from 30 MHz to 1 GHz. Adjustable dipole antennas are commercially available to cover this frequency range. Typically three antennas are required to cover the total frequency range. Antennas covering the 30 to 200 MHz, 200 to 400 MHz, and 400 to 1000 MHz frequency ranges are commercially available. These antennas must be mechanically adjusted to operate at a desired frequency and they exhibit desired gain and impedance characteristics over a relatively narrow frequency bandwidth. Thus, they are not appropriate for radiating or receiving a broad frequency spectrum or for swept frequency measurements. A broadband version of the dipole in the form of a biconical dipole antenna is more appropriate for broadband spectrum and swept frequency measurements. Biconical antennas covering the 30 to 200 MHz frequency range are commercially available from several sources. Broadband measurements in the 200 to 1000 MHz frequency range can be performed with log-periodic antennas, which are discussed in Section 7.5.4.

7.5.3 Monopole Antennas

Tuned monopole antennas are frequently used as alternatives to tuned dipole antennas in cases where the lengths of the dipoles create clearance problems or prevent the desired positioning of the antenna. These problems are normally encountered at relatively low frequencies (30 - 100 MHz) when vertical polarization is desired. Under these conditions, the antenna must be operated in the vertical position and the length of a tuned dipole frequently exceeds the ceiling clearance. In addition, the center of the dipole antenna must be located one-half the antenna length plus some clearance above the floor or gound reference. The use of a tuned monopole reduces the antenna length to one-half the dipole length and makes it possible to locate the base of the antenna close to the ground reference.

Non-tuned, electrically-small monopole antennas are also used at low frequencies when sensitivity is not a major concern. Short monopole antennas with adjustable impedance-matching baluns for use over the 10 KHz to 30 MHz frequency range are commercially available from several sources.

7.5.4 Log-Periodic Antennas

The log-periodic antenna is an array of overlapping dipoles capable of operating over a wide frequency range. Bandwidths of 10-to-1 are quite common. These antennas are used extensively as both radiators and receptors in the 200 MHz to 1000 MHz frequency range. While log-periodic antennas exhibit relatively constant gain and impedance characteristics over a wide frequency range, it should be noted that the phase center of the array moves along the structure as a function of frequency. This characteristic introduces some phase distortion in a broadband spectrum (i.e., a pulse spectrum) when the antenna is used as a radiator or receptor. In addition, the electrical position of the antenna changes with frequency. However, these antennas are very appropriate for swept frequency measurements and for radiating or receiving signals over a wide frequency range when relative phase is not important.

7.5.5 Summary of Commercially Available Antennas

Typical characteristics of commercially available antennas applicable to hardness maintenance and surveillance tests and inspections are listed in Table 7.5-1. Several typical suppliers of these antennas are also listed in the table.

7.6 COUPLERS

A major problem associated with the development of a direct injection test setup is the development of a coupling technique for injecting the excitation signal into the system under test. The coupler must be designed so

TABLE 7.5-1

TYPICAL CHARACTERISTICS OF COMMERCIALLY AVAILABLE ANTENNAS

TYPE	FREQUENCY RANGE	GAIN dBi	VSWR (MAX)
LOOP	100 Hz - 50 KHz	VARIABLE	
LOOP	10 KHz - 30 MHz	VARIABLE	
SHORT MONOPOLE	10 KHz - 30 MHz	VARIABLE	
BICONICAL DIPOLE	30 MHz - 200 MHz	VARIABLE	
ADJUSTABLE DIPOLE	30 MHz - 200 MHz	≈ 2	
ADJUSTABLE DIPOLE	200 MHz - 400 MHz	≈ 2	NA
ADJUSTABLE DIPOLE	400 MHz - 1 GHz	≈ 2	
LOG PERIOD	100 MHz - 1 GHz	5-8	2:1
LOG PERIOD	200 MHz - 1 GHz	5-7	2:1
DOUBLE-RIDGED HORN	200 MHz - 1 GHz	9-15	2:1

TYPICAL ANTENNA SUPPLIERS	
AEL, INC.	LANSDALE, PA
AILTECH INSTRUMENT DIV.	LOS ANGELES, CA
ELECTRO-MECHANICS CO.	AUSTIN, TX
ELECTRO-METRICS	AMSTERDAM, NY
SCIENTIFIC-ATLANTA, INC.	ATLANTA, GA

that it provides a reasonable coupling efficiency while ensuring that the coupled signal meets the requirements of the test. In addition, the coupler must provide sufficient isolation between the excitation source and the injection point so that the impedance of the source and interconnecting wiring does not significantly influence the operation of the system or subsystem under test.

Three basic types of couplers are used in direct injection testing: resistive, capacitive, and inductive. Resistive coupling to individual wires of a cable bundle or to individual terminals in a distribution or interface panel can be accomplished through a resistive matrix as shown in Figure 7.6-1. The values of the resistors used in the coupling matrix should be selected to present a reasonable load impedance to the excitation source and simulate the normal impedance values between the individual wires. The resistive coupling method may be used with shielded and unshielded conductors. With unshielded conductors, a cable tray, conduit, or the grounding system is used for the return path. One disadvantage of this coupling method is that one end of the cables being driven must be disconnected and the system under test may not be in its normal operating mode.

In cases where both ends of the cable(s) under test must remain connected to maintain the system in normal operation, capacitive or inductive coupling techniques must be utilized. Discrete capacitive coupling is conceptually similar to resistive coupling and requires the selection of a capacitance value which is a compromise between interface isolation and coupling efficiency. An example of a discrete capacitive coupling technique is shown in Figure 7.6-2(a). This technique uses a number of capacitors to couple the test source to the individual wires in a wiring bundle. The values of the capacitors are selected to provide low series impedances to the injected signal while presenting high shunt impedances to the desired signals on the system wires. The values of the resistors shown in the diagram are selected to present a reasonable load impedance to the test signal source. A distributed capacitive coupling technique is illustrated in Figure 7.6-2(b). A conductive sleeve is placed over a length of the wire(s) under test. The sleeve acts as one plate of the coupling capacitor while the individual wires act as the second plate. The achievable capacitance values are limited to about 20 pF/ft. It is difficult to achieve large capacitance values unless long sleeves are used, and thus this technique tends to be inefficient at low frequencies.

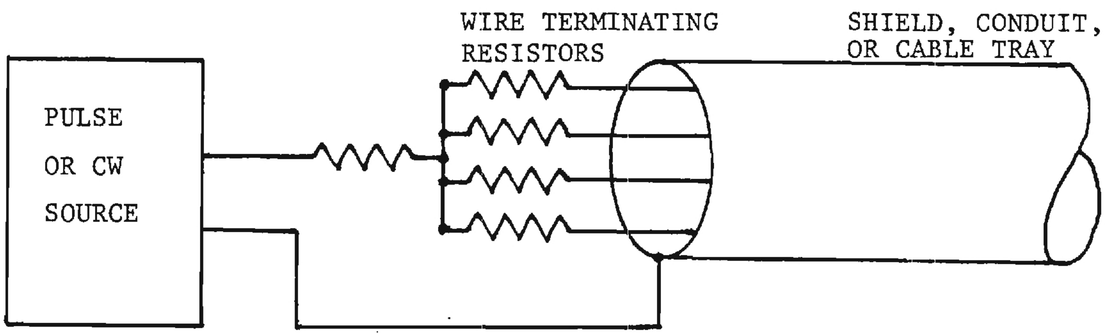
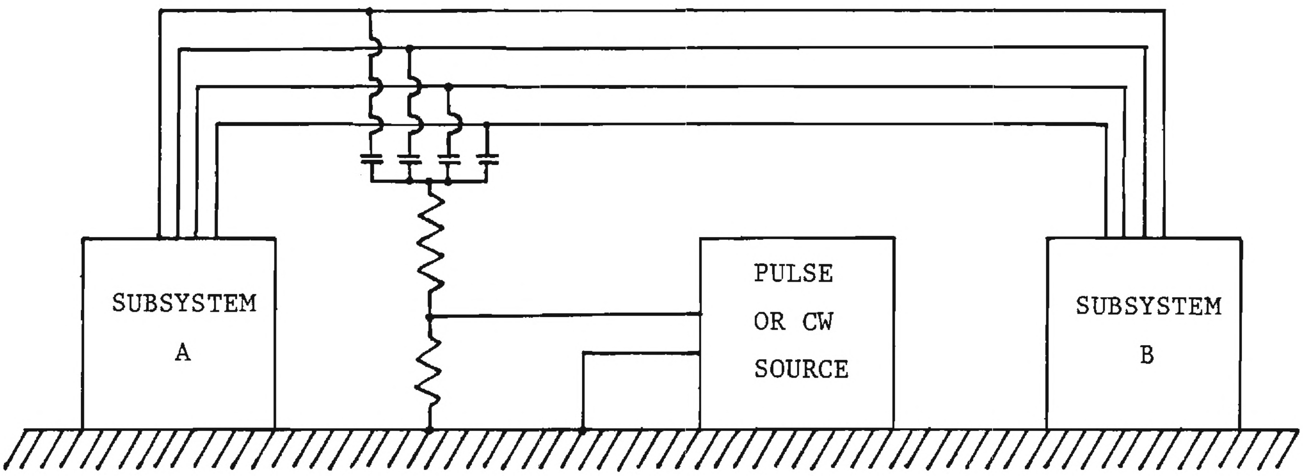
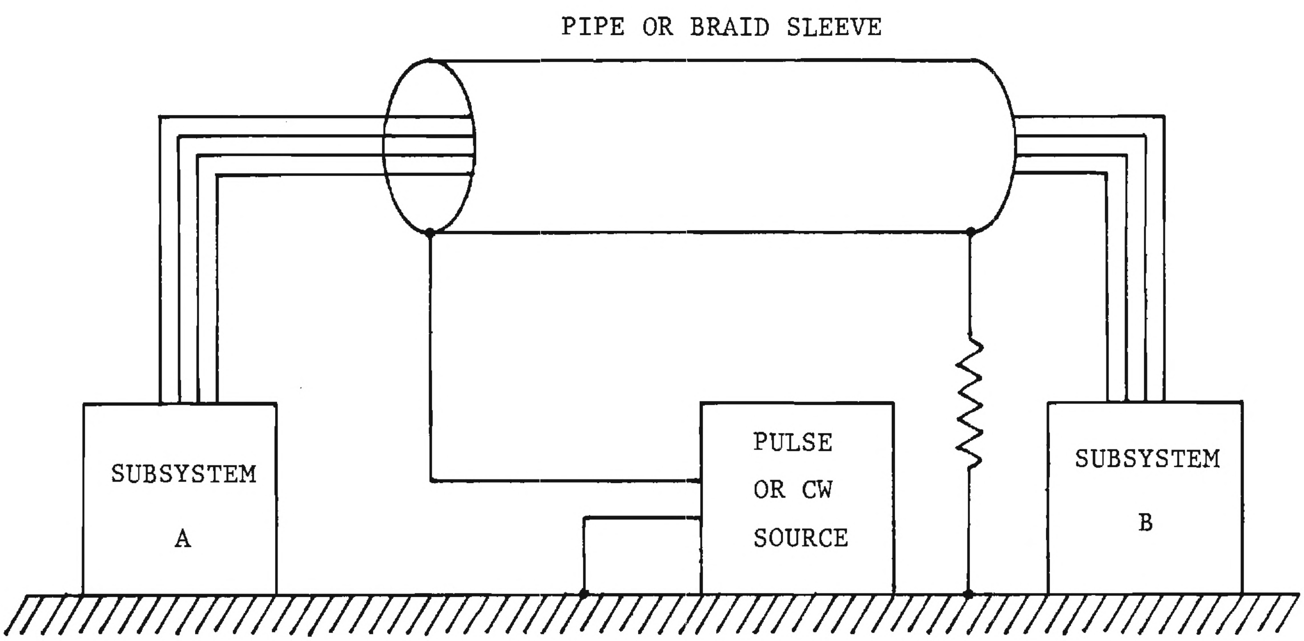


Figure 7.6-1. Resistive Coupling Matrix.



(A) DISCRETE CAPACITIVE COUPLING



(B) DISTRIBUTED CAPACITIVE COUPLING

Figure 7.6-2. Discrete and Distributed Capacitive Couplers.

Both discrete and distributed inductive couplers may be used to inject the excitation signal onto system cables. An example of a discrete inductive coupling technique is shown in Figure 7.6-3(a). This technique utilizes the transformer action between a primary formed by the test source output and a secondary formed by the wire(s) under test. This transformer action is enhanced by surrounding the primary and secondary wires with a ferrite torodial core. A distributed inductive coupling technique is illustrated in Figure 7.6-3(b). Several ferrite cores are located at intervals over a significant length of the wiring bundle under test, forming a distributed transformer coupling between the test source and the wires under test. This type of coupling more realistically simulates the coupling of an EMP transient to the system wiring.

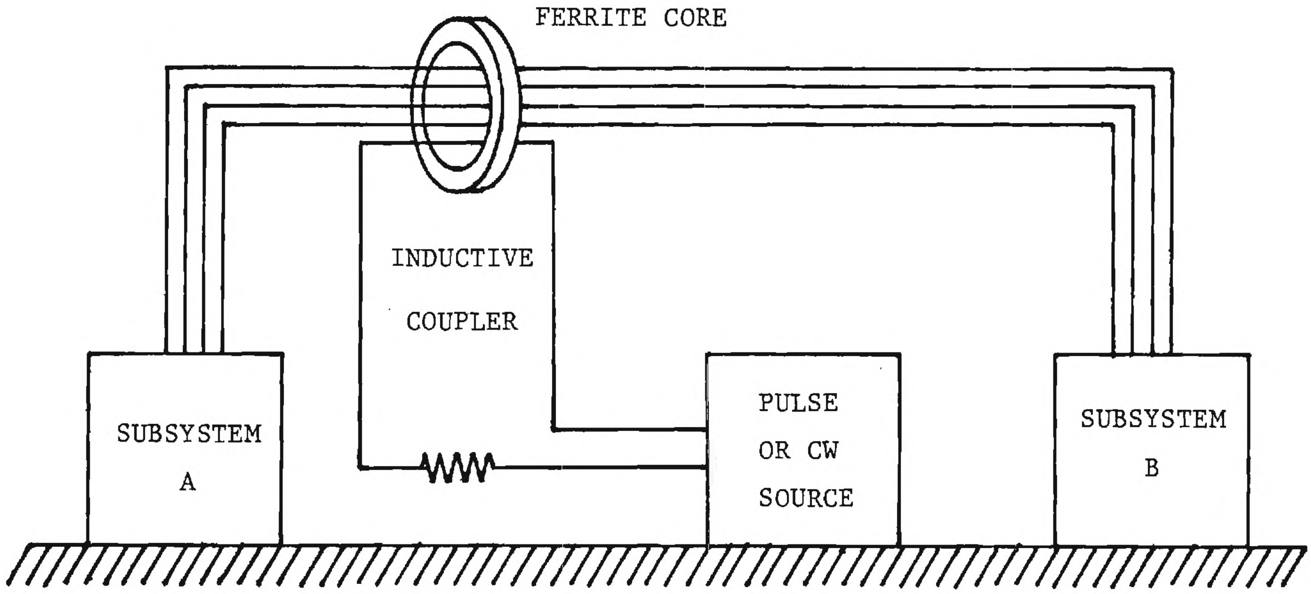
The inductive coupling techniques are particularly attractive for system testing because the ferrite cores can be split and clamped around cables without disconnecting, removing insulation from, or rerouting the system cables.

7.7 PROBES

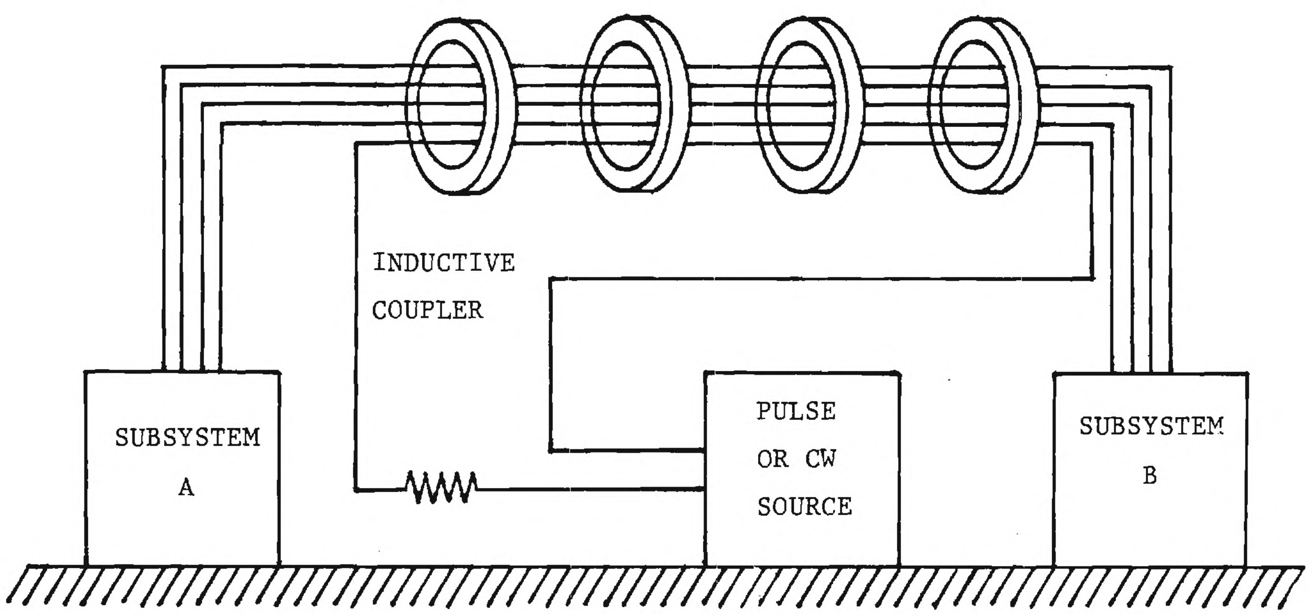
Both voltage and current probes are required to measure the currents and voltages that result at selected points in a system in response to the test excitation. A wide variety of both voltage and current probes are commercially available so that a probe to meet almost any set of measurement conditions can usually be found.

7.7.1 Voltage Probes

Voltage at selected points in the system under test is usually measured with a voltage probe used in conjunction with an oscilloscope, R.F. voltmeter, or an equivalent instrument. There are two basic types of voltage probes: single-ended and differential. Most commercially available voltage probes are single-ended types used to measure the voltage between a selected point and some reference plane such as a chassis, cable shield, or system ground reference. A differential voltage probe is used to measure the voltage between two selected points in a system. The differential probe is basically two single-ended probes connected to give an output that is the difference



(A) DISCRETE INDUCTIVE COUPLER



(B) DISTRIBUTED INDUCTIVE COUPLER

Figure 7.6-3. Discrete and Distributed Inductive Couplers.

between the voltages at the two points ($V_1 - V_2$). Thus, the differential probe is a three-terminal network with the third terminal to be connected to a common reference. The two types of voltage probes are illustrated schematically in Figure 7.7-1.

In order for the differential probe to respond only to the differential voltage, the two single-ended voltage circuits must have identical impedance and response characteristics. Any unbalance in the two halves of the probe will cause a common mode response (i.e., the probe output will contain some response from $V_1 + V_2$). This parameter of a probe is characterized by a common mode rejection ratio (CMRR). The common mode rejection ratio is defined as:

$$\mathrm{CMRR} = 20 \log \frac{V_{diff}}{V_{com}} \text{(in decibels)}$$

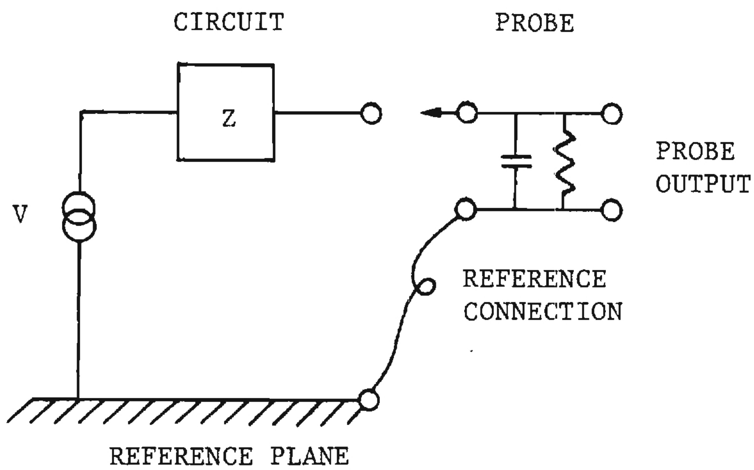
where:

$$V_{diff} = V_1 - V_2$$
$$V_{com} = V_1 + V_2$$

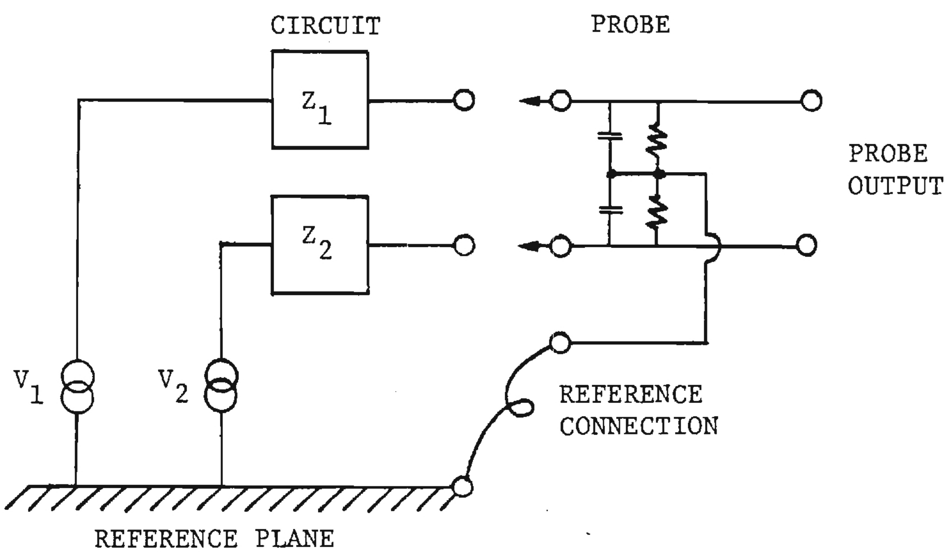
Commercial differential voltage probes exhibit common mode rejection ratios that range from 70-80 dB in the low-kilohertz frequency range to 30-40 dB in the 50 MHz range.

It is apparent from Figure 7.7-1 that the response of any voltage probe is influenced by the impedance of the probe, the impedance of the voltage source being measured, and the impedance of the reference connection. Commercial probes are available with high input impedances (high resistance, small capacitance) that have subnanosecond response times. Internal attenuation is often incorporated in voltage probes to allow them to be used to measure higher levels of voltage.

Typical characteristics of commercially available voltage probes and several voltage probe suppliers are listed in Table 7.7-1.



(A) SINGLE-ENDED VOLTAGE PROBE



(B) DIFFERENTIAL VOLTAGE PROBE

Figure 7.7-1. Basic Types of Voltage Probes,

TABLE 7.7-1

TYPICAL CHARACTERISTICS OF COMMERCIALLY AVAILABLE VOLTAGE PROBES

TYPE	INPUT IMPEDANCE	ATTENUATION	RISETIME (nS)	BANDWIDTH (MHz)	DC VOLTS MAX
SINGLE-ENDED	10M Ω/12.5pF	10X	1.4	250	500
SINGLE-ENDED HIGH VOLTAGE	100M Ω/3pF	1000X	1.4	250	20K
SINGLE-ENDED FET	10M Ω/2pF 10M Ω/2pF	10X 100X	0.7 0.7	500 500	200 200
DIFFERENTIAL FET/AMP	1M Ω/10pF 10M Ω/3pF	1X 10X	3.5 3.5	100 100	25 250

TYPICAL VOLTAGE PROBE SUPPLIERS	
EG&G	ALBUQUERQUE, NM
HEWLETT-PACKARD	PALO ALTO, CA
PHYSICS INTERNATIONAL, INC.	SAN LEANDRO, CA
TEKTRONIX, INC.	BEAVERTON, OR

7.7.2 Current Probes

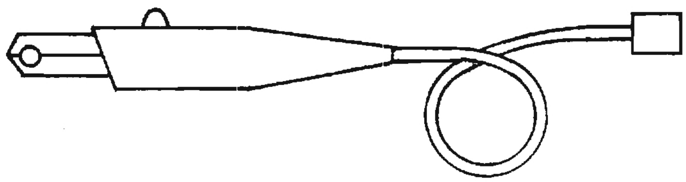
Current is usually measured with a current probe which is basically the secondary of a current transformer. The wire carrying the current to be measured serves as the transformer primary. A large variety of current probes are commercially available. Current probes are available in three configurations: snap-on, clamp-on and solid-loop. These configurations are illustrated in Figure 7.7-2. The snap-on probe shown in Figure 7.7-2(a) is normally designed to measure the current in a single wire. A split probe loop is mounted in the front end of the probe and can be opened and closed by means of a switch on the probe handle. The clamp-on probe shown in Figure 7.7-2(b) is in the form of a split loop. The two halves of the loop are hinged and a clamping mechanism is provided to clamp the probe around a single wire or a bundle of wires. When clamped around a wire bundle, the probe measures the bulk current in the bundle. Clamp-on probes are readily available with inside hole diameters ranging from 1.27 cm to 12.5 cm. The solid-loop probe shown in Figure 7.7-2(c) is in the form of a solid loop. The use of this type probe requires that one end of the wires to be measured by disconnected and threaded through the probe loop. Solid-loop probes are readily available with inside hole diameters ranging from 0.5 cm to 27 cm.

Typical characteristics of commercially available current probes and several current probe suppliers are listed in Table 7.7-2.

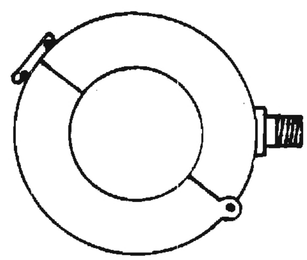
7.8 BROADBAND AMPLIFIERS

Amplifiers are frequently used in EMP hardness testing to increase the levels of the excitation to be applied to the system under test and to increase the levels of the signals sampled by the test probes. In most cases, the amplifiers are required to have a very broad bandwidth. If pulsed signals are to be amplified, the amplifier must exhibit constant gain and linear phase response over the entire pulse frequency spectrum in order for the pulse waveform to not be distorted. The pulse rise time that an amplifier is capable of reproducing is related to the bandwidth of the amplifier by the following expression:

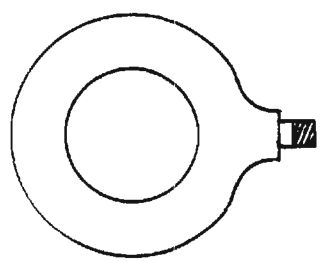
$$\text{Rise time (seconds)} = \frac{0.35}{\text{Bandwidth(Hertz)}}$$



(A) SNAP-ON CURRENT PROBE



(B) CLAMP-ON CURRENT PROBE



(C) SOLID-LOOP CURRENT PROBE

Figure 7.7-2. Current Probe Configurations.

TABLE 7.7-2

TYPICAL CHARACTERISTICS OF COMMERCIALLY AVAILABLE CURRENT PROBES

TYPE	OUTPUT (Volts/Amp.)	HOLE DIA. (cm)	BANDWIDTH	RISETIME (ns)	MAX CURRENT	
					RMS	PEAK
SNAP-ON	5	0.4	30 KHz - 1 GHz	0.35	0.45A	100 A
	1	0.4	1.2 KHz - 100 MHz	3.50	2.5 A	100 A
CLAMP-ON	5	1.270	100 KHz - 200 MHz	1.75	4.6 A	30 A
	5	3.175	10 KHz - 100 MHz	3.50	30 A	100 A
	1	3.175	1 MHz -1000 MHz	0.35	14 A	50 A
	0.001	6.665	10 KHz - 100 MHz	3.50	100 A	5000A
	2	6.665	20 Hz - 30 MHz	10.50	140 A	200 A
	0.001	10.160	10 KHz - 100 MHz	3.50	75 A	6000A
	0.006	12.700	10 KHz - 100 MHz	3.50	40 A	5000A
SOLID-LOOP	1	0.63	320 Hz - 175 MHz	2.0	2.5 A	100 A
	1	1.27	140 Hz - 35 MHz	10.0	5 A	500 A
	1	5.08	125 Hz - 17.5MHz	20.0	7.5 A	500 A
	0.1	8.89	40 Hz - 8.75MHz	40.0	140 A	5000A
	0.1	27.30	400 Hz - 7 MHz	50.0	120 A	5000A

TYPICAL CURRENT PROBE SUPPLIERS	
Ailtech Instrument Div.	Los Angeles, California
Atlantic Research	Alexandria, Virginia
Pearson Electronics, Inc.	Palo Alto, California
Tektronix, Inc.	Beaverton, Oregon

The low-frequency response of the amplifier determines the ability of the amplifier to faithfully reproduce the flat top of a pulse. For a wide pulse, the top will sag or droop if the low-frequency cutoff of the amplifier is not sufficiently low.

Broadband amplifiers are also frequently required for CW testing. When an amplifier is used in a swept-frequency test setup, the bandwidth of the amplifier must be sufficient to cover the frequency spectrum to be swept. In many cases, if there is any significant variation in the gain characteristics of the amplifier over the swept frequency range, the test data must be processed to compensate for the gain variation. This type data processing can be a very tedious and time consuming task. When an amplifier is used in a test setup where CW measurements are to be made at several discrete frequencies, it is desirable that the amplifier have a bandwidth sufficient to cover all the test frequencies so that it is not necessary to tune the amplifier and record the gain at each test frequency.

A large variety of broadband amplifiers are commercially available from a number of sources. These amplifiers have bandwidths that cover several octaves of frequency and output levels that range from milliwatts to 10 KW. The gain characteristics of the amplifiers are constant within 1 to 1.5 dB over their bandwidths. Typical characteristics of commercially available broadband amplifiers and some typical suppliers are listed in Table 7.8-1.

7.9 TELEMETRY EQUIPMENT

In many cases, it is necessary to locate the processing and recording instrumentation remote from the sampling probes in order to: (1) satisfy space limitations, (2) prevent the instrumentation from distorting the EMP simulation, or (3) prevent the EMP simulation from affecting the performance of the instrumentation. Under these conditions, it is necessary to transmit the sampled signals to the remote instrumentation. The signals can be transmitted via hard wire cables; however, the presence of long cables between the probes and remote instrumentation introduces the possibility of several problems. Unless the cables are extremely well shielded, there is the possibility that undesired signals from the environment will be coupled to the cables. Also, the presence of the cables may alter the system interaction with the EMP simulation. In addition, long cables will also introduce

TABLE 7.8-1

TYPICAL CHARACTERISTICS OF COMMERCIALLY

AVAILABLE BROADBAND AMPLIFIERS

TYPE	OUTPUT (watts)	FREQUENCY RANGE	GAIN (dB)	FLATNESS (dB)
Low-Power 2-25 Watts	2 2 10 25	30 Hz - 100 MHz 500 KHz- 450 MHz 10 KHz- 200 MHz 50 Hz - 100 MHz	40 35 40 45	$\pm$1.5 $\pm$1.5 $\pm$1.5 $\pm$1.5
Medium-Power 50-200 Watts	50 100 150 200	100 KHz-1,000MHz 10 KHz- 200 MHz 1 MHz- 200 MHz 10 KHz- 250 MHz	45 50 53 48	$\pm$1.5 $\pm$1.5 $\pm$1.5 $\pm$1.5
High-Power 500-10,000 Watts	500 1,000 2,000 5,000 10,000	10 KHz- 200 MHz 10 KHz- 200 MHz 10 KHz- 200 MHz 1 MHz- 100 MHz 10 KHz- 100 MHz	57 60 63 70 70	$\pm$1.5 $\pm$1.5 $\pm$1.5 $\pm$1.5 $\pm$1.5

Typical Amplifier Suppliers

Amplifier Research	Souderton, Pennsylvania
Eaton Corp., EID	Los Angeles, California
IFI	Farmingdale, New York
RF Power Labs, Inc.	Woodinville, Washington

frequency-sensitive attenuation and phase delay in the sampled signals, particularly at the higher frequencies. To circumvent these potential problems, nonconducting data links or telemetry systems are frequently used.

Three types of nonconducting telemetry systems are frequenctly used in EMP hardness testing. These systems use microwave radiation, dielectric waveguide, and fiber-optics data links. The three types of systems are illustrated in Figure 7.9-1. The microwave data link illustrated in Figure 7.9-1(a) requires the radiation of a microwave signal. The operating frequency is selected to be several times the highest frequency in the EMP simulation spectrum. The transmitting end of the data link, which is normally located in reasonably close proximity to the sampling probes, consists of a modulator, a microwave transmitter, and a directional (usually a horn) transmitting antenna. The type modulation may vary from simple single-channel AM to multi-channel FM-FM. The receiving end of the data link, located at the instrumentation site, consists of a directional receiving antenna, a microwave receiver, and a demodulator. The radiating microwave data link has the desirable characteristic that long transmission paths can be established, but the system has several disadvantages when compared to the other two types of data links. The physical size of the transmit end of the microwave data link with its transmit antenna and power source is significant and in some cases could alter the system interaction with the EMP simulation. For maximum coupling between the transmit and receive antennas, the antennas must be boresighted on a line-of-sight path between the two antennas. Even under these optimum coupling conditions, an appreciable propagation loss is suffered in coupling energy between the two antennas.

The dielectric waveguide data link illustrated in Figure 7.9-1(b) circumvents some of the disadvantages of the microwave data link. The configuration of the transmit and receive ends of the data link is the same as for the microwave data link, except that the transmit and receive antennas have been eliminated. A dielectric-rod waveguide is used as the transmission media between the two ends of the data link. Dielectric rod transmission systems have been successfully used over the 8 to 18 GHz frequency range with waveguide lengths in excess of 30 meters. Propagation losses less than 0.1 dB/ft have been obtained at frequencies above 12 GHz. Bending of the dielectric waveguide on a 3-meter radius does not noticeably affect system

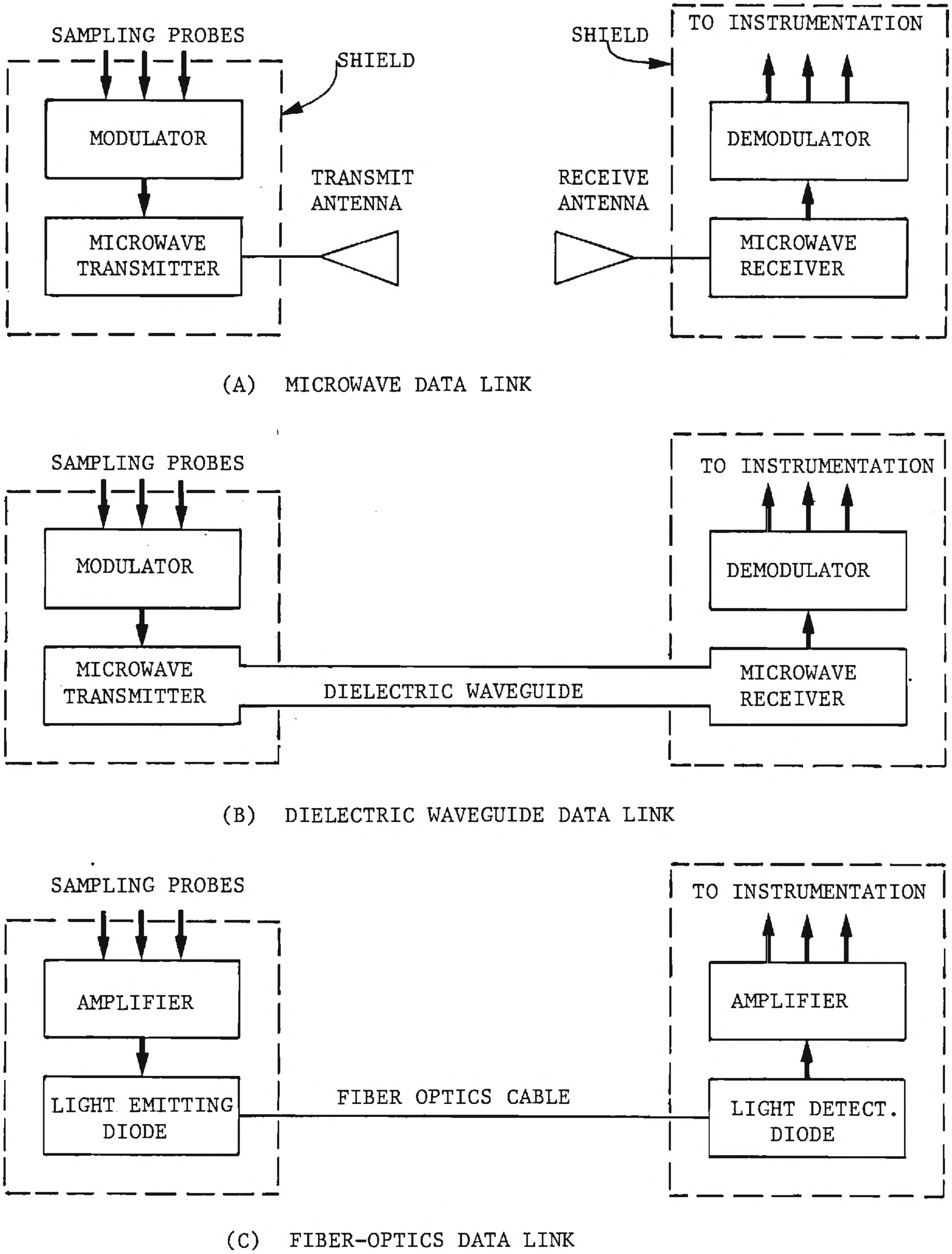


Figure 7.9-1. Nonconducting Data Links.

performance. For some applications, the dielectric waveguide data link has several advantages over the microwave radiating data link. The elimination of the transmit and receive antennas reduces the physical sizes of the link terminals and relaxes the restrictions on the location and orientation of the terminal equipment. The dielectrical waveguide significantly reduces the propagation losses over short links (less than 50 meters) relative to microwave links.

A nonconducting telemetry system can also be obtained by transmitting modulated light through a flexible fiber-optics cable as illustrated in Figure 7.9-1(c). The data to be transmitted is converted to modulated light by a light-emitting diode. The modulated light is coupled to the receive terminal of the data link through a flexible fiber-optics cable. A photodiode in the telemetry receiver converts the received modulated light back into the original data format. Some of the attractive features of the fiber-optics data link are: small physical size of the terminal equipment, lower power requirements, low attenuation, and a flexible transmission path between the terminals. Fiber-optics telemetry systems with bandwidths up to 140 MHz and cable lengths up to 2,000 meters are commercially available.

All three types of telemetry systems are commercially available from a number of sources. Typical characteristics of commercially available telemetry systems and several typical suppliers are listed in Table 7.9-1.

7.10 SHIELDING MEASUREMENT EQUIPMENT

The shielding effectiveness of the outer shield of a facility or enclosure is a primary consideration in a hardness maintenance and surveillance program. The shielding effectiveness may be measured using either time-domain measurements or frequency-domain measurements. A methodology or standard that recommends equipment for time-domain shielding effectiveness tests has not been formalized. The methodology in MIL-STD-285, entitled "Attenuation Measurements for Enclosures, Electromagnetic Shielding for Electronic Test Purposes, Method of," dated 25 June 1956 is used for frequency-domain measurements. This standard specifies test and equipment set-ups to perform shielding tests. A more recent document that is used as a guide for frequency-domain shielding effectiveness tests is entitled,

TABLE 7.9-1

TYPICAL CHARACTERISTICS OF COMMERCIALLY AVAILABLE TELEMETRY SYSTEMS

TYPE	BANDWIDTH	MAX. LINK DISTANCE (METERS)
MICROWAVE	10KHz - 150MHz	UNLIMITED
DIELECTRIC WAVEGUIDE	10KHz - 150MHz	30-50
FIBER-OPTICS	10Hz - 140MHz	30-2,000

TYPICAL TELEMETRY SYSTEM SUPPLIERS

AYDIN VECTOR DIV.	NEWTON, PA
DEVELCO, INC.	SUNNYDALE, CA
EG&G	ALBUQUERQUE, NM
HUGHES AIRCRAFT CO.	CULVER CITY, CA
MERET, INC.	SANTA MONICA, CA
MICON	BRICKTOWN, NJ

"Proposed IEEE Recommended Practice for Measurement of Shielding Effectiveness of High-Performance Shielding Enclosures," No. 299, dated June 1969.

A facility or enclosure can be exposed to either plane-waves, electric near-fields, or magnetic near-fields. A facility or enclosure exposed to an exoatmospheric burst will be exposed to a plane wave. However, small enclosures located within a facility are likely to be exposed to either magnetic or electric near-fields, particularly for frequencies below 1 GHz. A correction factor* must be applied to the MIL-STD-285 near-field measurements to obtain the corresponding shielding effectiveness of a facility or enclosure to a plane wave.

Shielding effectiveness tests of large-complex facilities are performed in the time-domain to simulate the waves generated by an exoatmospheric burst. Ideally, the facility is exposed to a plane wave that illuminate the entire structure. Frequency-domain (CW) measurements may be performed on large facilities, but must be accomplished on a piecemeal basis. The CW measurements do not evaluate shielding efectiveness for plane waves, but currents are excited on the shield to test for poor seams, damaged gaskets, etc.

7.10.1 Time-Domain Shielding Measuremements

Transportable wave simulators, such as those described in Section 7.1.4, are used to perform time-domain shielding effectiveness tests on large facilities. The simulator may be either a radiating or bounded wave type. The simulators are transported to the facility and assembled on site. The radiating simulator is assembled adjacent to the facility, while the bounded wave simulator is assembled over the facility. Facility acceptance tests should be performed using a threat-level simulator.

A typical configuration used to perform time-domain shielding measurements on a facility or enclosure is shown in Figure 7.10-1. The simulator is located at a sufficient distance so that a plane wave impinges on the facility. Trade-offs between the wave uniformity and the wave amplitude may

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*Villaseca, Eduardo and William Blackwood, Carl Davis, and William Getson, "An Investigation of the Validity of Applying MIL-STD-285 to EMP Shielding Effectiveness," DNA 4411F, dated 15 April 1977.

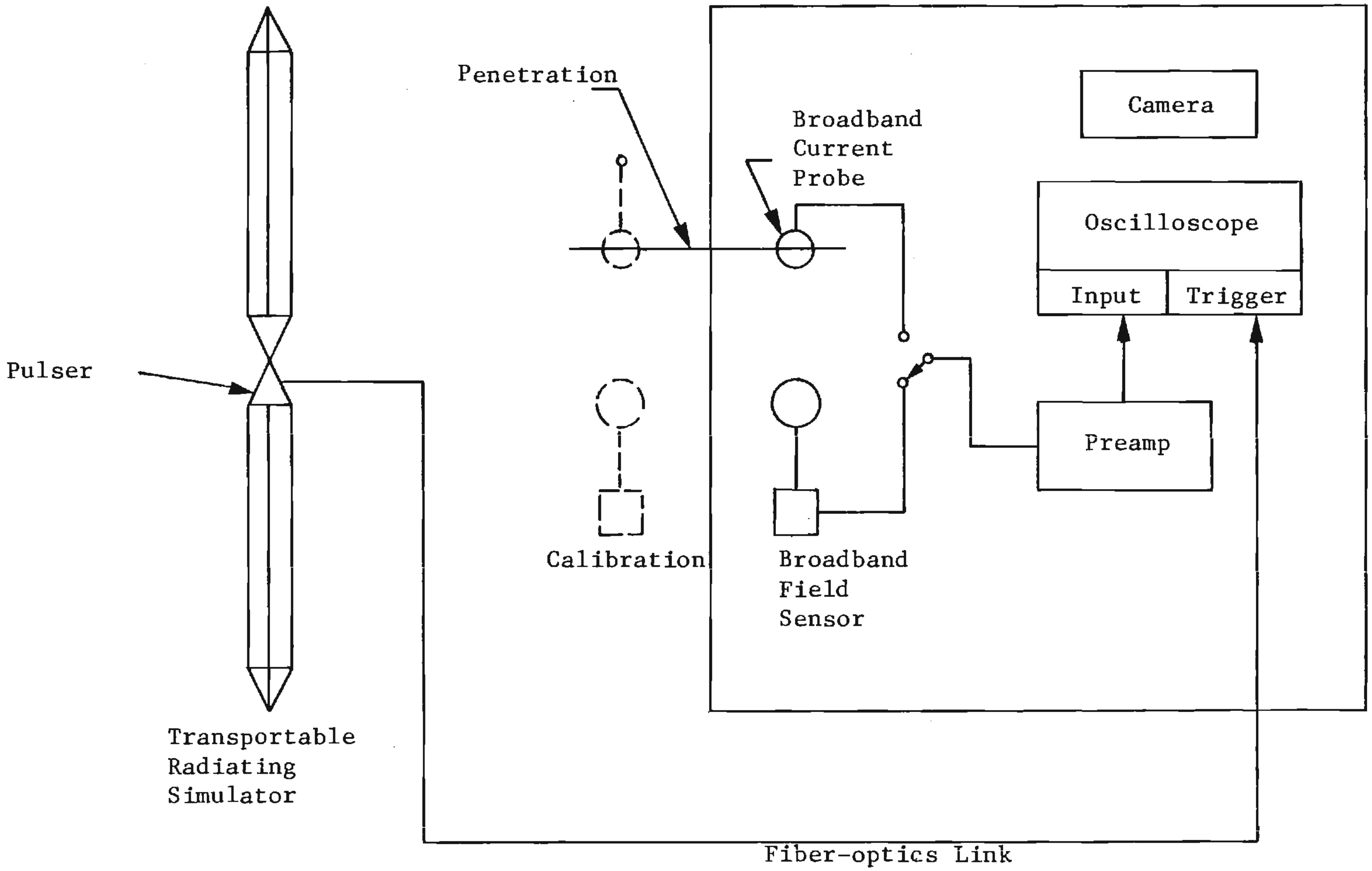


Figure 7.10-1. Time-Domain Shielding Measurements.

be necessary for some large facilities. Within the facility or enclosure being tested, an oscilloscope, either analog or digital, is used to record the response to the transient wave generated by the simulator. The oscilloscope must be triggered in synchronization with the simulator pulser. As shown in Figure 7.10-1, a fiber optic link from the pulser is one means of providing the trigger for the oscilloscope. A field sensor, either an electric or magnetic type, is used to measure the field level inside the facility or enclosure. Currents induced on shield penetrations are examined using current probes. Fields external to the facility are also measured using the same sensors and equipment as used for the internal measurements. The amplitude diffference between the two measurements is equal to the shielding effectiveness.

7.10.2 Frequency-Domain Shielding Measurements

The equipment used to perform frequency-domain shielding measurements is based on recommendations in MIL-STD-285 and the Proposed IEEE Recommended Practice No. 299. Equipment and procedures are specified to determine the shielding effectiveness over the frequency ranges from 100 Hz to 20 MHz and from 300 to 1000 MHz. Where only an estimate of shielding effectiveness is desired, single frequency tests are recommended within three standard frequency ranges: (1) 14 - 16 kHz, (2) 13 -18 MHz, and (3) 850 - 950 MHz. Measurement results for these three standard frequency ranges form a uniform basis to compare the performances of various shielding enclosures.

For the lower frequency ranges (100 Hz to 20 MHz), magnetic loops are employed. In the UHF range (300 - 1000 MHz), dipoles are employed.

In the lower frequency ranges, tests using both large and small loops are employed. The large-loop test procedure simulates, in some degree, a magnetic field encompassing the entire enclosure. As such, it provides a measure of the overall performance in the low-frequency region from 100 Hz to 200 kHz. Provisions for two large-loop tests are made, but the one involving the entire enclosure, where access to all walls of the enclosure is possible, is recommended. Where limited access exists, an alternate test is delineated which requires access to only one wall. The small-loop test procedures simulate, in some degree, the fields from sources near the enclosure walls. This test also provides an in situ measure of the effectiveness of certain construction features, such as bonds between adjacent panels or gaskets. This procedure may also be used to measure the effectiveness of shielding doors. The small-loop test procedure covers the frequency range from 100 Hz to about 20 MHz.

For the UHF range (300 - 1000 MHz), dipole-to-dipole tests are delineated. The effect of a nearby source on all portions of accessible wall areas is determined by one test procedure. The effect of distant sources is assessed by combining measurement results on all accessible portions of the enclosure.

The single-frequency measurements in the three above-mentioned frequency ranges should provide a good guide for the relative performance of enclosures, or doors, in all ranges. However, tests using other frequencies pertinent to the specific installation should be considered. No recommended tests procedures are noted for frequencies between 20 - 300 MHz, owing to the sensitivity of the test results to small variations in measurement procedures. Large resonant type antennas are required. Enclosure cavity resonances in this region often give rise to uncorrelatable results. Where tests in this region are desired, the practices noted for the small-loop tests or the UHF tests may be used as a guide.

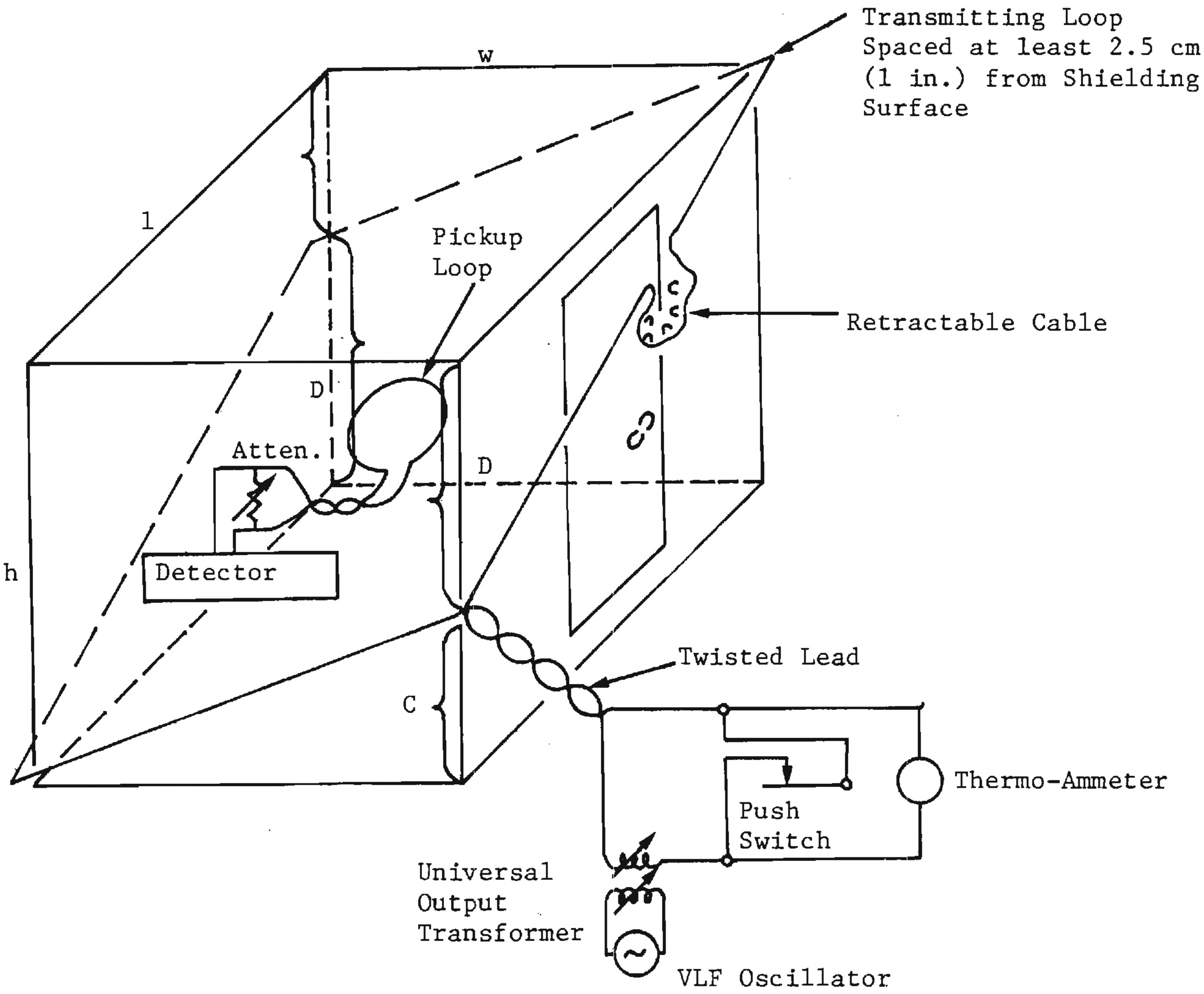
7.10.2.1 Low Frequency Loop Tests. The large-loop test configuration and equipment as given in the Proposed IEEE Recommended Practice No. 299 are shown in Figure 7.10-2.

The test magnetic field is generated by current in a large planar loop encircling the enclosure at a spacing of at least one inch from the outer shielding material. Such a loop around a rectangular object forms a parallelogram. As shown in Figure 7.10-2, the obtuse angle vertices are positioned away from the floor and ceiling by distances C and D which are proportional to the horizontal distances from the respective acute vertices:

$$C = \left(\frac{w}{l + w} \right) h$$

$$D = \left(\frac{l}{l + w} \right) h$$

It may be noted that $C = h - D$ and $D = h - C$. In these equations, l, w, and h are the enclosure dimensions of length, width and height, respectively.



NOTES: $C = \frac{w}{l+w} h$

$D = \frac{l}{l+w} h$

ALSO $C = h-D$

$D = h-C$

Pickup loop in plane of large loop or center of enclosure

Figure 7.10-2. Large-loop Test Setup.

The large loop consists of a single turn of stranded, insulated copper wire, preferably No. 18 AWG "hook-up" wire. The loop wire can be fastened by means of rubber suction cups, masing tape, or both. This wire can be fastened to the exterior surface of the enclosure or to nearby objects, such as building walls, so that the wire is at least 2.5 centimeters (1 inch) away from the outer wall of the enclosure.

In order to avoid obstruction of the door by the large loop, a retractable cable such as a test probe lead or telephone cord may be utilized as part of the loop at the jamb edge of the door, as shown in Figure 7.10-2. For maximum convenience, the large-loop orientation can be selected so that this cable is placed on the upper portion of the door.

A conventional one-watt output RC oscillator is usually adequate to supply the loop current in the 14 - 16 kHz band, provided the impedance mismatch is minimized at the lower frequencies by a step-down transformer, such as a universal output transformer. Higher power sources and resonant matching may be required at higher frequencies. Current through the large loop may be measured by the voltage drop across a known carbon resistor or by using a thermo-ammeter, with a parallel momentary-open switch to protect it against overload.

The detector may be either a field intensity meter equipped with a pickup loop for the measurement of magnetic fields, or a combination of pickup loop and high input impedance RF voltmeter. The detector should be capable of indicating 300 microvolts.

For a field intensity meter, the calibration and meter readings are normally given in terms of an equivalent electric field E_{eq2} on the basis of plane-wave propagation. The corresponding magnetic field H_2 is then obtained from the expression

$$H_2 = \frac{E_{eq2}}{\eta} = \frac{E_{eq2}}{120\pi}$$

where η is the wave impedance of free space, and for the numerical form, H_2, is expressed in amperes per meter when E_{eq2} is given in volts per meter.

If a pickup loop, high-impedance voltmeter combination forms the detector, the pickup loop should consist of 11 turns of closely spaced insulated wire on a 0.762 meter (30-inch) diameter form. The loop should be connected to a volt-meter (or amplifier-voltmeter combination) of high input impedance only. The input impedance must always be large compared to the inductive reactance of the loop.

For the high-impedance voltmeter detector, the field H_2 in amperes-per-meter at the center of the enclosure is given by

$$H_2 = \frac{V_{induced}}{2\pi f N_1 A \mu}$$

and for the suggested loop, the above equation reduced to:

$$H_2 = 2.5 \times 10^4 \left(\frac{V_{induced}}{f} \right)$$

where

$V_{induced}$ = induced voltage in volts
f = frequency in hertz
N_1 = number of turns on the pickup loop (11)
A = area of pickup loops (0.456 square meters)
μ_o = permeability of air ($4\pi \times 10^{-7}$ henry/meter).

The small loop test configuration and equipment as given in the Proposed IEEE Recommended Practice No. 299 are shown in Figure 7.10-3.

The test magnetic field is generated by current in an 0.30 meter (12-inch) diameter transmitting loop. The loop may be constructed from a single turn of No. 6 AWG copper wire. A conventional laboratory test oscillator is usually adequate to supply the loop current by a suitable step-down transformer such as a universal output-to-voice-coil transformer in the VLF band. Higher power sources and resonant matching may be required at higher frequencies.

The detector may be a field intensity meter or a high impedance voltmeter which measures the voltage induced in a pickup loop identical to the 0.30 meter (12-inch) transmitting loop.

A modified equipment configuration, that is sometimes used for the small loop test, is shown in Figure 7.10-4. Commercially available loop antennas are to make the shielding effectiveness measurements. The loop coupling is calibrated external to the facility or enclosure. The same two loops are then used to measure the coupling through the shield.

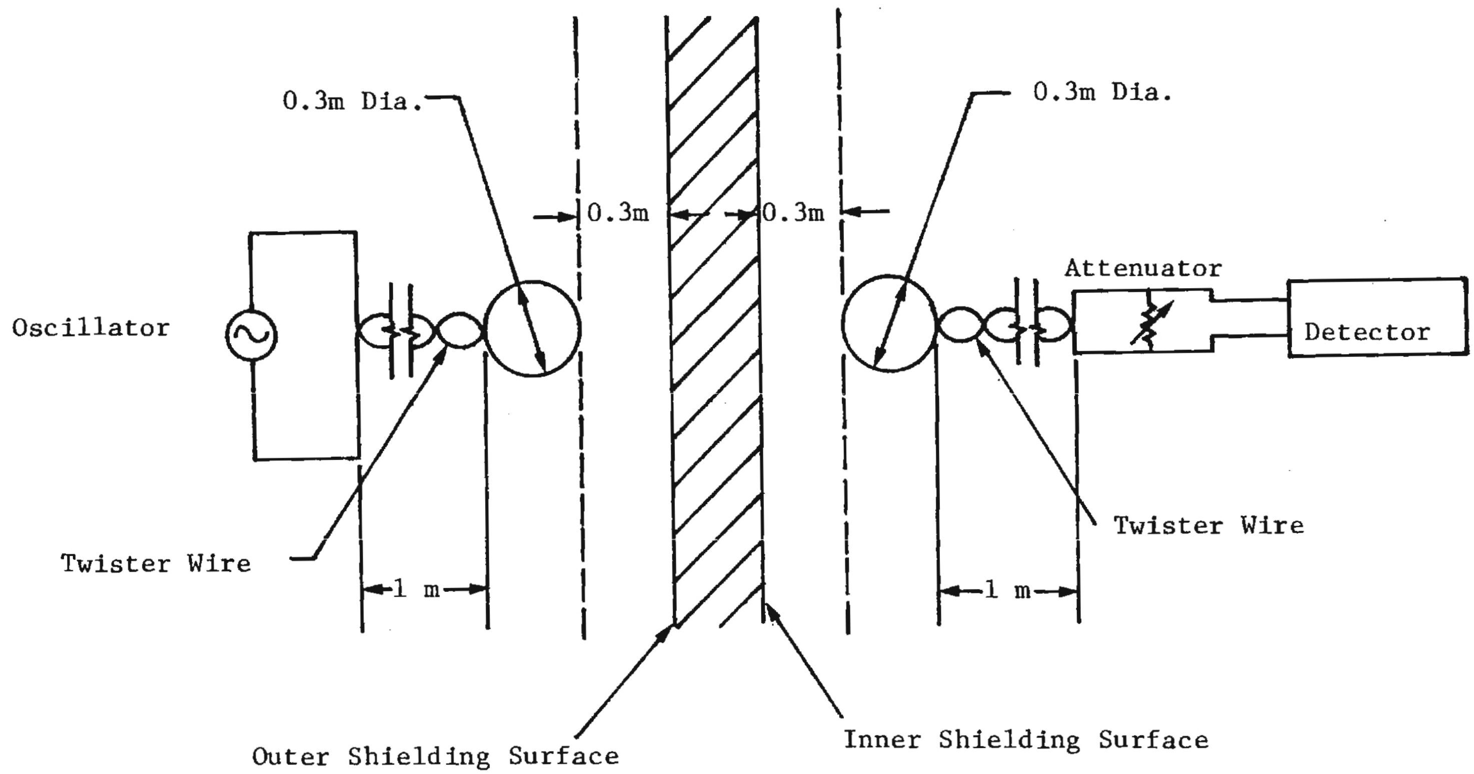


Figure 7.10-3. Small-loop Test Setup.

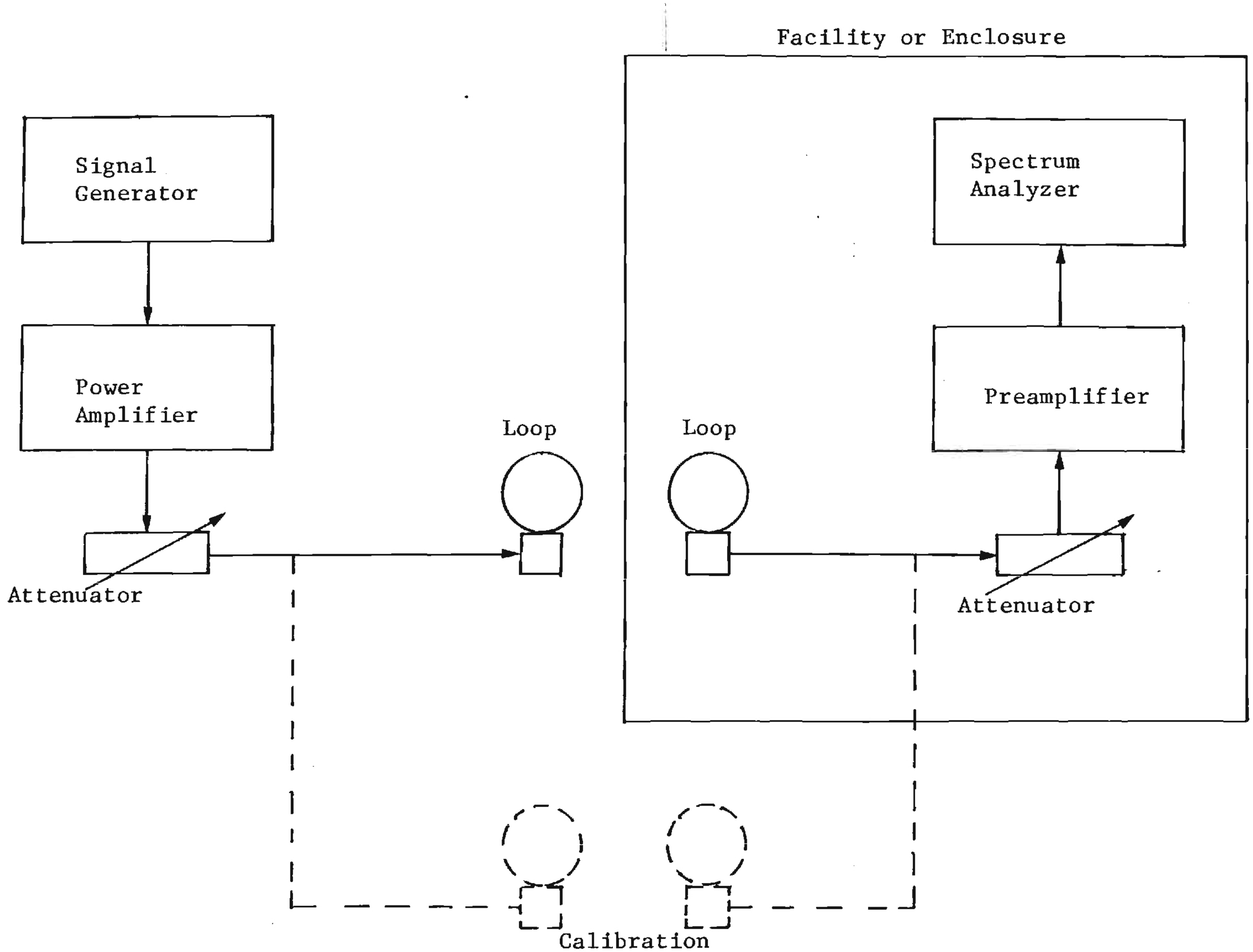


Figure 7.10-4. Modified Equipment Configuration for Small-Loop Shielding Tests.

7.10.2.2 UHF Tests. The UHF test configuration and equipment as given in the Proposed IEEE Recommended Practice No. 299 are shown in Figure 7.10-5.

Because of the high attenuation usually introduced by the shielding enclosure, a signal generator capable of delivering at least 10 watts into a matched load may be required. The generator should be connected to a 75 Ω unbalanced to a 300 Ω balanced transformer. The output of the 300 Ω side of the transformer should be connected to a half-wavelength, balanced, folded dipole antenna which is resonant at the test frequency. Other forms of providing a balanced drive, and which preclude radiation from the cable, are acceptable but should be described in the test report. The cable should be perpendicular to the dipole and should be at least two meters or two wavelengths long, whichever is greater.

The detecting antenna is an electric dipole whose over-all electric length is one-eighth of a wavelength (so as to minimize impedance change problems at the test frequency). The output of the receiving antenna is connected through a balanced-to-unbalanced transformer (balun) via an antenna cable, such as RG-9 or equivalent. The antenna cable is connected to a field intensity meter. The field intensity meter should be preceded by an attenuator, if one is not contained within the field intensity meter. The field intensity meter should be located well away from the vicinity where the tests are being conducted. The coaxial cable, except in regions very close to the walls or floors of the enclosure, must always be perpendicular to the axis of the electric dipole. The field intensity meter should have a sensitivity of -80 dBm or better, and should be insulated from the conductive portions of the enclosure. A modified equipment configuration that is sometimes used for the UHF tests is shown in Figure 7.10-6. Commercially available broadband antennas are used in place of the folded dipoles. A signal generator and power amplifier generate high-power levels to drive the antennas. The fields interior to the facility or enclosure are measured using a preamplifier and spectrum analyzer.

Tracking generators are sometimes used in place of the signal generator in Figure 7.10-6. The tracking generator is a signal source whose RF output frequency tracks the spectrum analyzer tuning. The combination of the tracking generator and spectrum analyzer gives an improved dynamic range which may exceed 120 dB. The key to this large dynamic range is the precision

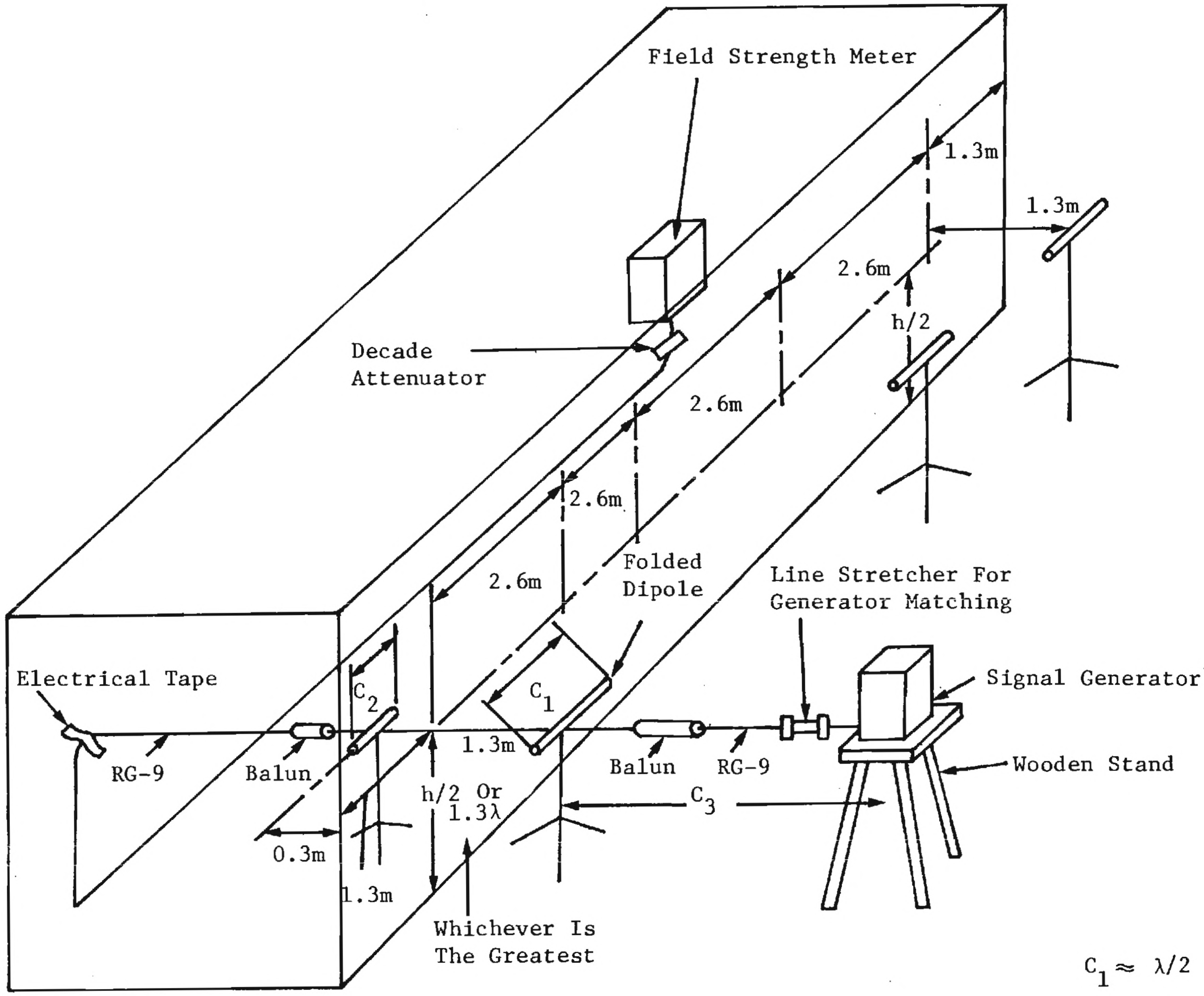


Figure 7.10-5. UHF Measurement Setup.

$C_1 \approx \lambda/2$

$C_2 \approx \lambda/8$

C_3 = 2m Or 2λ
Whichever is Greater

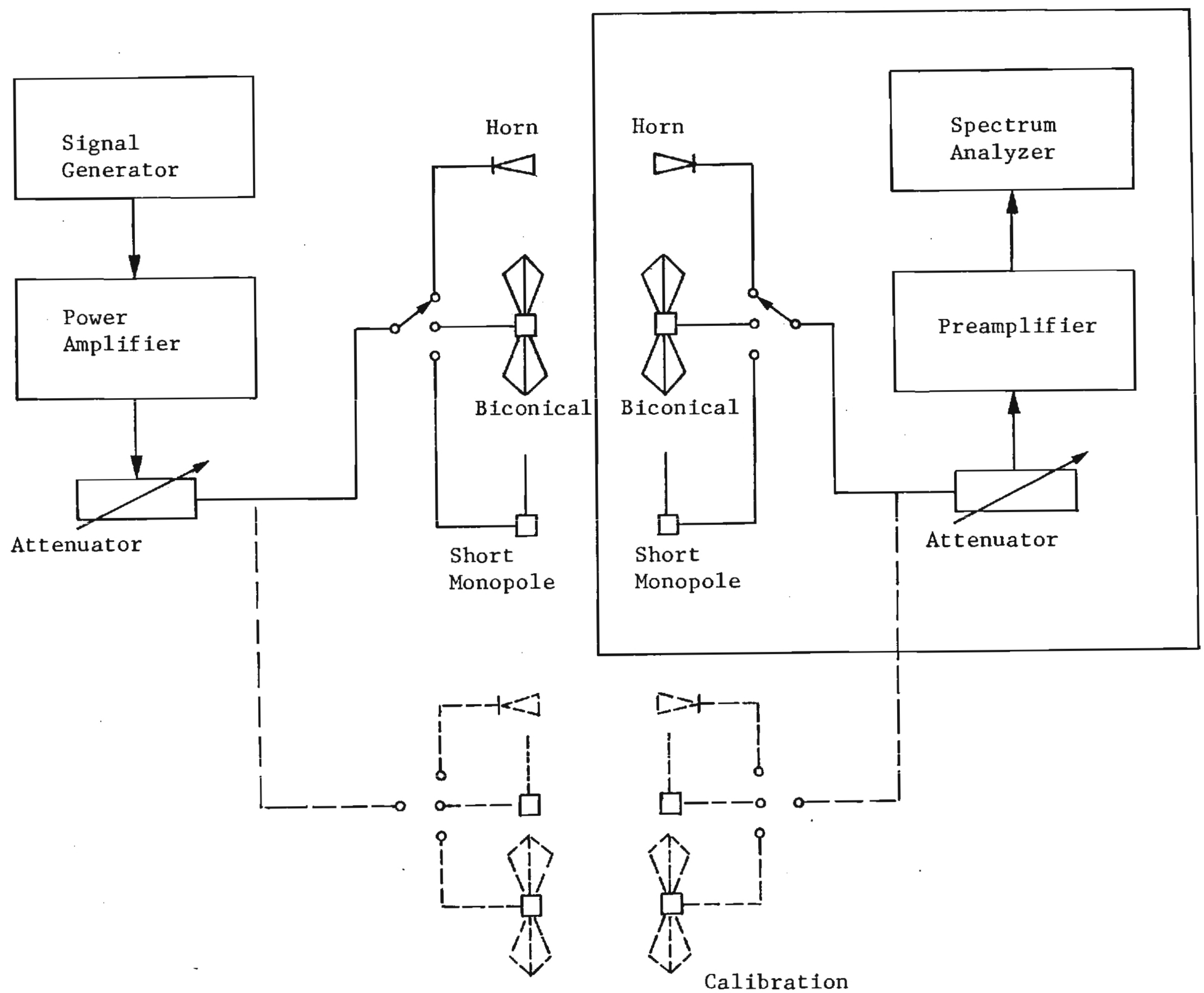


Figure 7.10-6. Modified Equipment Configuration for UHF Tests.

tracking which exists between the analyzer tuning and the generator RF output frequency. This tracking permits over-driving the analyzer mixer to the 1 dB compression level, without displaying the distortion products. The tracking generator signal is always within the spectrum analyzer bandpass, and all distortion products, whether generated in the spectrum analyzer or tracking generator, are outside the analyzer passband and thus are not displayed. The tracking generator does not add any broadband noise, thus the spectrum analyzer's sensitivity is essentially unaffected.

For the equipment configuration in Figure 7.10-6, the tracking generator is placed inside the facility/enclosure with the spectrum analyzer and control connections are made between the two instruments. A coaxial cable must be routed from the tracking generator output to the power amplifier input. This coaxial cable must penetrate the facility/enclosure shield. Precautions must be taken to insure that this cable penetration does not compromise the shielding effectiveness measurements.

7.11 DIRECT INJECTION EQUIPMENT

Energy may be injected into a system under test without creating electromagnetic fields in free space. Currents and voltages can be indirectly (inductive and capacitively coupled) or directly (hard wired or resistively coupled) injected onto conductors or conductor shields of a system to evaluate the EMP hardness characteristics of the system. Direct injection techniques are utilized in a number of hardness maintenance and surveillance test procedures to evaluate the shielding effectiveness of system cables and the performance of protective devices and penetration/interface treatments.
The amount of energy coupled to individual cables of a system is a very small percentage of the energy in the radiated EMP environment. Hence, direct injection tests can be performed with much lower-power energy sources than would be required for radiated tests. Several methods for coupling a signal onto a cable or cable shield are currently used. The method chosen for a particular test will depend on such factors as the configuration and function of the cable circuit, its impedance, the type of shielding, the power levels and waveform characteristics involved, and the accuracy requirements for the test. For tests in which the cable shield is to be driven, the shield current is of primary interest. For tests in which unshielded conductors or core

conductors inside a shield are driven, the voltage between the conductor and the system ground is usually of primary interest.

7.11.1 Current Injection on Cable Shields

One of the simplest concepts for coupling a signal to a cable shield by means of a uniform field over a significant length of the shield is to make the cable shield the center conductor of a coaxial transmission line as illustrated in Figure 7.11-1(a). With this configuration, the outside of the cable shield and the inside of the concentric return path form a coaxial transmission line with a characteristic impedance of:

$$Z_o = 138 \log \frac{D}{d} \quad \text{(assuming air dielectric)}$$

where:

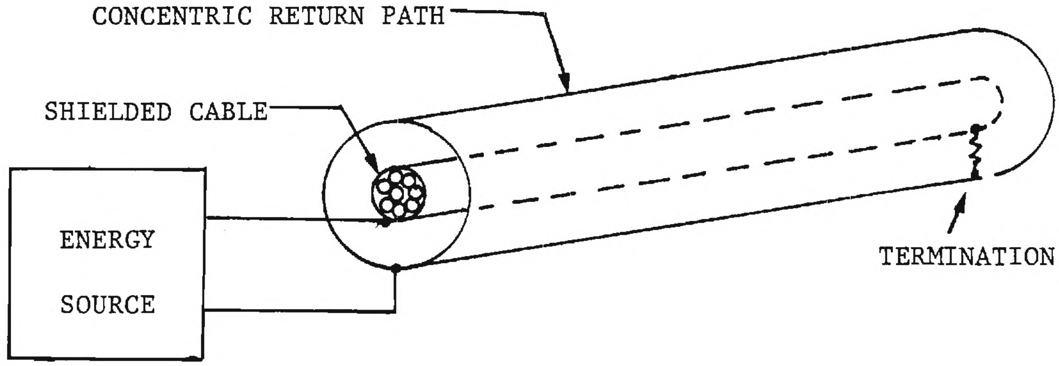
D = inside diameter of return path cylinder, and

d = outside diameter of cable shield

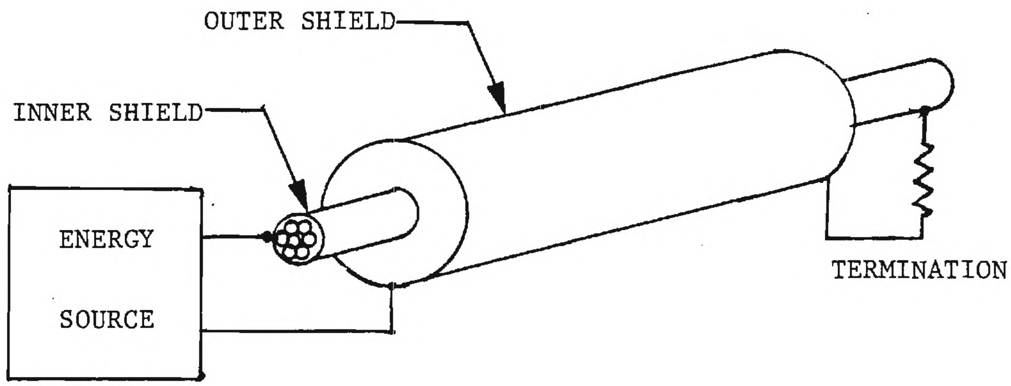
If this structure is terminated in its characteristic impedance, a uniform current having a value of V/Z_o amperes will be induced in the shield over the length of the transmission line.

In most cases, it is not practical to install a concentric return path around installed shielded cables to utilize this coupling technique. However, the technique can be used on double-shielded cables where the two shields are insulated from each other. This technique, illustrated in Figure 7.11-1(b), is very efficient in terms of driver power requirements because only the current on the inner shield must be simulated, and this current is much smaller than the current that would be coupled to the outer shield. The inner shield is driven as the center conductor of a coaxial transmission line, and the outer shield serves as the concentric return path.

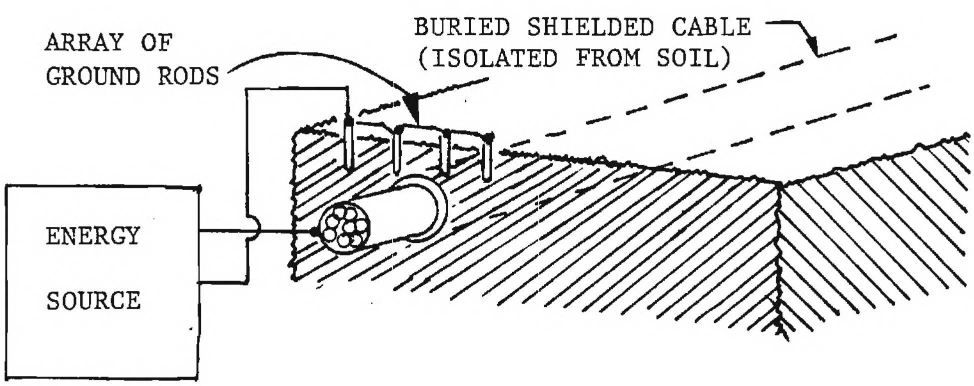
The coaxial transmission line driver technique may also be used on buried shielded cables where the shield is insulated from the soil. The configuration is illustrated in Figure 7.11-1(c). The cable shield, insulation, and soil form a natural coaxial geometry which can be used to induce current on the cable shield. The cable shield is driven as the center conductor of a coaxial transmission line and the soil serves as the concentric return path. It is necessary to establish a low impedance connection to the soil at the



(A) COAXIAL TRANSMISSION LINE SHIELD DRIVER



(B) DOUBLE-SHIELD TRANSMISSION LINE DRIVER.



(C) BURIED CABLE TRANSMISSION LINE DRIVER

Figure 7.11-1. Coaxial Transmission Line Cable Shield Drivers.

driving point so that most of the source voltage is applied to the transmission line. This can be accomplished with an array of ground rods in the vicinity of the driving point.

An example test configuration to drive the inner shield of a double-shielded cable is illustrated in Figure 7.11-2. The driver consists of a 3 μF, 50 kV capacitor bank charged from a 50 kV dc power supply and switched onto the inner shield of the cable with a 40 kV ignitron. Because it is desired to drive the core wires through the inner shield, the inner shield must be well shielded at the driving end of the cable to prevent direct coupling from the driver to the core wires. Thus, the inner shield is extended with a metal enclosure to shield the core wires.

The shields of installed system cables are often driven by current transformers as illustrated in Figure 7.11-3(a). This technique is very attractive for periodic maintenance and surveillance tests because clamp-on ferrite cores and current transformers are available which can be clamped around the cables without disturbing the cable system. However, it should be noted that this technique does not give a distributed coupling by a uniform field over a significant length of shield as is obtained with the coaxial transmission line driver. Thus, the current transformer coupling technique is not as good a simulation of the EMP environment coupling to the shield as the coaxial transmission line coupling technique. Some degree of distributed coupling can be obtained by locating several current transformers along the length of the shield as illustrated in Figure 7.11-3(b).

7.11.2 Direct Injection on Conductors

Injection of excitation upon signal-carrying conductors is often considerably more difficult than injection on cable shields because of the need to devise a coupling technique that permits the excitation to be injected without "loading" the system circuit and, thereby, altering its performance and its response to the excitation. Any of the resisitive, capacitive, or inductive coupling techniques discussed in Section 7.6 may be used to inject excitation on signal-carrying conductors.

An example of a test configuration to inject a pulse onto the primary power lines of a facility by means of capacitive couplers is shown in Figure 7.11-4. The driver was designed to inject a 50 kV pulse at the commercial

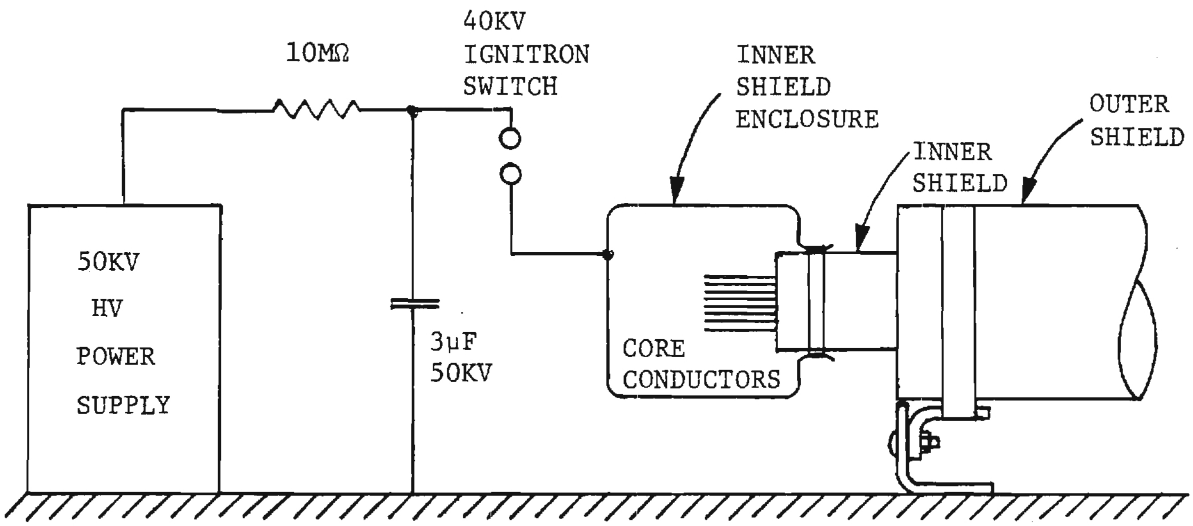
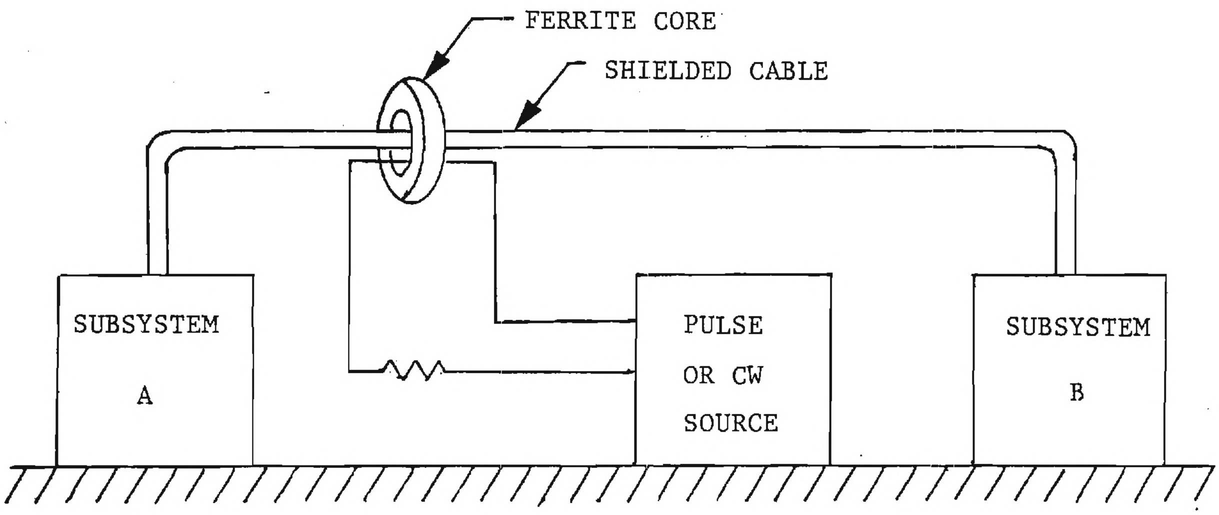
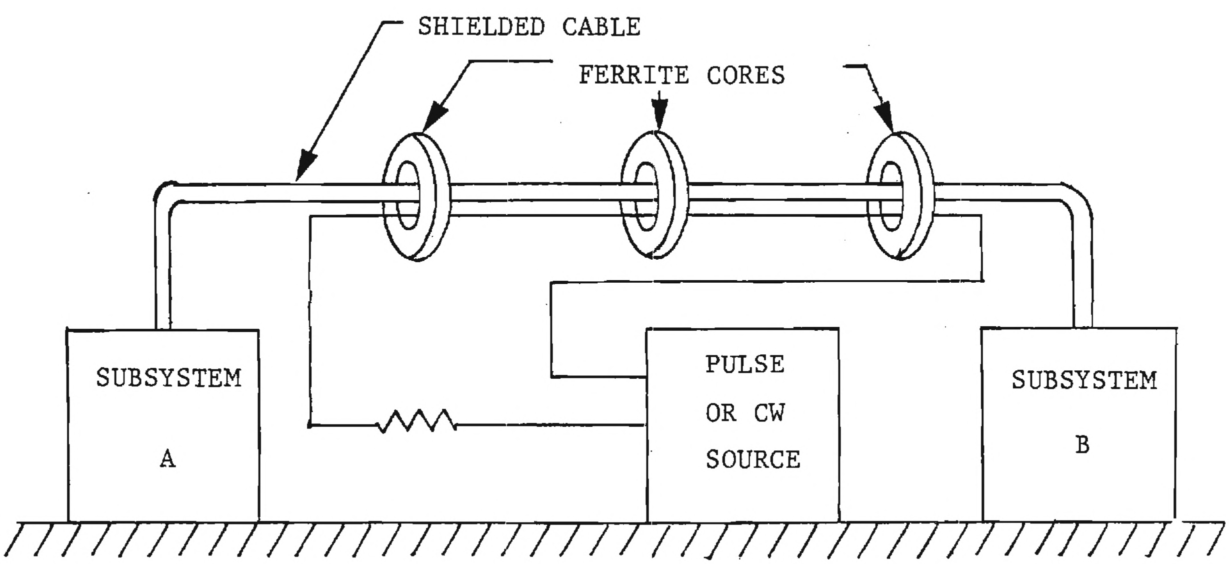


Figure 7.11-2. Example Pulse Driver For Double-Shielded Cable.



(A) CURRENT TRANSFORMER SHIELD DRIVER



(B) DISTRIBUTED CURRENT TRANSFORMER SHIELD DRIVER

Figure 7.11-3. Current Transformer Cable Shield Drivers.

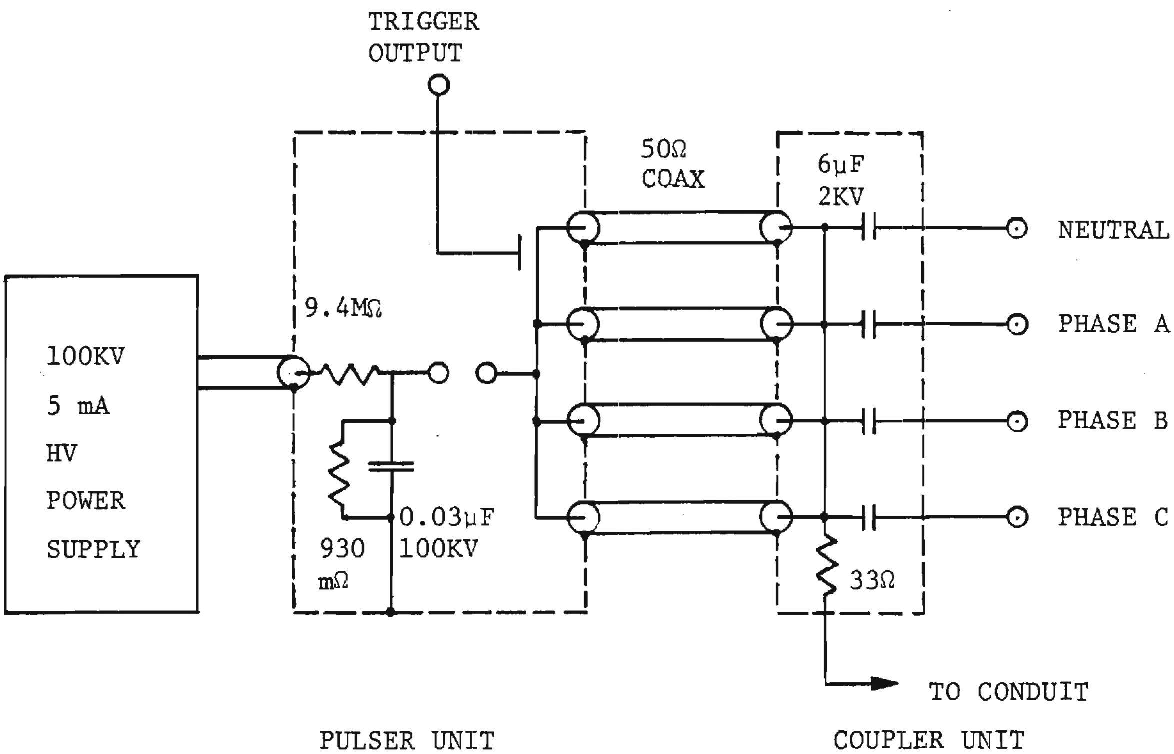


Figure 7.11-4. Example Power Line Pulser And Coupler.

power weatherhead of a facility. The design criteria for the driver were as follows:

Peak voltage	$\geq$ 50 kV
Rise Time	$\leq$ 10 ns
Pulse Shape	Exponential Decay
Decay Time	$\geq$ 500 ns
Repetition Rate	$\geq$ 1 pps

The driver consists of three units: a high voltage power supply, a pulser unit, and a coupler unit. The power supply and the pulser are located remote from the power lines, and the coupler unit is located at the commercial power weatherhead. The pulser unit output is delivered to the coupler unit through four 50-ohm coaxial cables. These cables are connected in parallel, and a single conductor could have been used. However, to provide pulser flexibility, separate cables were provided for each power line conductor.

The pulser unit contains a 0.03 μ F charging capacitor in the form of a series stack of low-inductance pancake capacitors mounted in a concentric cylindrical housing, a 9.4 megohm charging resistor, and a spark-gap switch. A 930 megohm bleeder resistor is shunted accross the charging capacitor to discharge the pulser when it is not in operation, and a capacitive coupler provides a trigger output coincident with the pulse discharge. The value of the charging capacitor was selected to satisfy the pulse decay requirements when the pulser is loaded by the impedance of the power lines (approximately 40 ohms) and the load resistor (33 ohms) in the coupler unit. The value of the charging resistor was selected to satisfy the pulse repetition rate and thecurrent limitation of the high voltage power supply. The charging capacitor is charged through the charging resistor until the spark-gap switch fires. At this point, the capacitor discharges through the output cables and coupler unit into the power lines.

The coupler unit is designed to efficiently deliver the output from the pulser to the power lines without significantly loading the power lines. Four 6 μF capacitors are operated in parallel to deliver the pulser output equally to all four conductors of the power system. The 6 μF coupling capacitors will pass that portion of the pulse spectrum above 200 Hz with little distortion, and at the same time, will allow only approximately 0.25 ampere of 60-Hz current to flow back into the coupler unit. A 33-ohm load resistor is provided in the coupler unit which is in parallel with the power-line impedance. This load resistor reduces the effect of any impedance variation of the power lines on the pulse characteristics and reduces the effects of any reflections from the power lines.